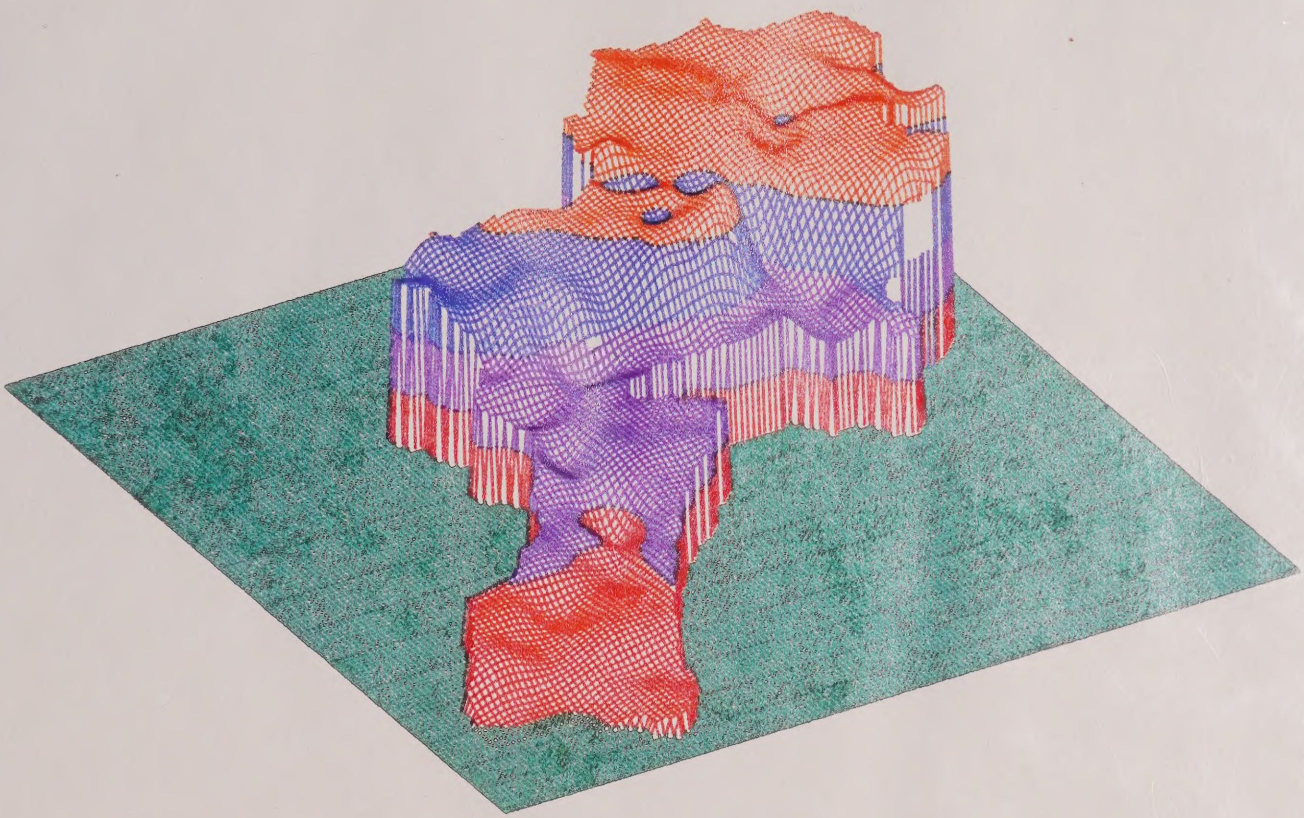
GROUNDWATER RESOURCES OF THE CREDIT RIVER WATERSHED



MINISTRY OF ENVIRONMENT AND ENERGY
Environmental Monitoring And Reporting Branch

PREFACE

This report describes the general occurrence, quantity and quality of the groundwater resources in the Credit River watershed and does not attempt to address in detail specific situations or local issues. The report is intended to provide the basic hydrogeologic information that can be used for the wise planning of the groundwater resources of the watershed.

Toronto, April 1994.

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INTRODUCTION

GROUNDWATER AND WATERSHED PLANNING

Groundwater is vital to the health and economic well-being of all the people of Ontario and it is one of our most valuable resources. Groundwater provides a reliable water supply of high quality water that has nearly constant temperature to domestic, public, agricultural, commercial and industrial users. It is often the primary source of rural and urban water supplies in Ontario, and is an important component of streamflow, especially during dry weather periods.

In the past, surface water and groundwater were treated as two separate resources and their interactions were often examined in a superficial manner. This attitude is changing as more water managers are coming to the conclusion that groundwater is an essential component of watershed hydrology and, therefore, must be an integral part of any comprehensive watershed management plan. The full consideration of the groundwater resources in a watershed planning exercise is not an academic endeavour, but is an essential undertaking that has social, financial, environmental and ecological implications.

Appropriate land use planning in a watershed requires a good understanding of its groundwater resources. To meet the expanding demand for water supply and to protect environmentally sensitive areas in the watershed from haphazard development, it is critical to identify the important aquifers, delineate the recharge and discharge areas, assess the quantity and quality of the groundwater resource, and define the links between groundwater and surface water.

PURPOSE AND SCOPE OF THE STUDY

Groundwater studies can be conducted on a regional, watershed, sub-watershed or site scale. The scale of a study determines the type and amount of data required, the degree of accuracy that is acceptable, the applicable techniques, and the associated costs.

The purpose of this study is to evaluate the occurrence, quantity, and quality of the groundwater resources in the Credit River watershed. This includes:

- the compilation, analysis and interpretation of existing information related to physiography, topography, drainage, climate, and soils;

- the assessment of the bedrock and overburden geology of the watershed and its surrounding area;

- the identification of the geologic conditions under which various groundwater flow systems operate;

- the determination of the hydrogeologic parameters of the various hydrogeologic units;

- the delineation of principal areas of recharge and discharge;

- the evaluation of the long-term groundwater recharge and discharge on a monthly and annual basis as part of water budget analysis; and

- the examination of the surface water and groundwater hydrochemistry and its change over time.

SOURCES OF INFORMATION

The study made extensive use of data contained in the Water Well Information System (WWIS) of the Ministry of Environment and Energy. The WWIS is a computer database that was designed in 1972. The system provides for the easy input and retrieval of data describing the characteristics of water wells drilled in Ontario between 1946 and 1984. The WWIS contains approximately 400,000 water well records.

The WWIS indicates that there are 4953 water wells constructed in the Credit River watershed prior to 1984. Of these wells, 1180 are in the overburden, 2751 are in the bedrock, 403 are of unknown type, and 799 have inaccurate locations. To enhance the available database, a field program was initiated to identify the geographic coordinates and surface elevations of an additional 1500 wells constructed within the watershed after 1984 (Map 1).

A water well record contains information on up to 212 parameters including:

- surface elevation;

- location: geographic coordinates, county or district, township, borough, city, town or village, lot, concession, and watershed;

- geology: geologic formations encountered during drilling;

- water: depth at which water was found, depth to static level, and the kind of water encountered in terms of being fresh, salty, sulphurous or containing iron or gas;

- pumping test and well yield;

- well construction details: casings, screens, plugs, and seals; and

- date of well completion.

Recent advances in the area of Geographic Information Systems (GIS) make it feasible to consider a large amount of data, to present these data on thematic maps, and to conduct numerous analyses and interpretations within a short time frame. The Regional Analysis By Intelligent Systems On A Microcomputer (RAISON) is such a GIS system. RAISON, which was originally developed by the National Water Institute and the University of Guelph, has been extensively modified to accommodate the specific characteristics of the WWIS database and to perform numerous hydrogeologic analyses for the area under study.

Limited field investigations were made of the geology and hydrogeology of the watershed. Climatic data, streamflow records, and data on surface water and groundwater chemistry within the watershed and surrounding areas were used to supplement field studies.

PREVIOUS INVESTIGATIONS

The Palaeozoic rocks underlying the area were previously described by Caley (1940), Bolton (1953 and 1957), Hewitt (1969), Liberty (1969), Liberty and Bolton (1971), and Sanford (1969). Information on the Palaeozoic rocks underlying the area is contained in the water well records maintained by the Ministry of Environment and Energy, and in oil and gas well records maintained by the Ministry of Natural Resources.

The Pleistocene features and deposits of the area have been mapped by Chapman and Putnam (1951), Karrow (1963, 1968 and 1971), Cowan and Sharpe (1973), White (1975), and Cowan (1976). Agricultural soils have been mapped by Hoffman et al (1953, 1963 and 1964), and by Gillespie et al (1971).

Numerous technical reports dealing with local issues related to water supply, landfill design, and sewage works have been prepared by various consulting firms. These reports contain useful information on the hydrogeology of a number of local areas within the watershed.

ACKNOWLEDGEMENTS

This study was carried out under the general supervision of Mr. E. Piche', Director, and Dr. K. Roberts, Manager, Drinking water Section, both of the Environmental Monitoring and Reporting Branch, Ontario Ministry of Environment and Energy.

Appreciation is expressed to the Credit Valley Conservation Authority for their financial contribution to this study. In particular, appreciation is due to Mr. K. Owen, Acting General Manager and to Ms. H. Breton, Water Resources Engineer for their support, cooperation and valuable assistance.

The assistance of Dr. D.R. Sharpe of the Geological Survey of Canada and Mr. D.W. Finley of Northwood Geoscience Ltd. in compiling and digitizing the surface and bedrock geology maps of the watershed is greatly appreciated.

Co-operation received from the Regional offices of this Ministry, municipal officials, and residents of the Credit River watershed is gratefully acknowledged.

GEOGRAPHY

LOCATION

The Credit River watershed is located in Southern Ontario on the north side of Lake Ontario between Longitudes 79^0 32′ W and 80^0 12′ W, and Latitudes 43^0 29′ N and 43^0 57′ N (Figure 1). The watershed has an area of about 795 km^2 at Erindale, a total length of about 90 km extending from Orangeville in Dufferin County to Port Credit on Lake Ontario, and a width that varies between 9 and 23 km.

The watershed is bounded on the south by Lake Ontario, on the east by Etobicoke Creek and the Humber River, on the north by the Nottawasaga River, and on the west by the Grand River and the East Oakville Creek. A number of small watercourses in the vicinity of Lake Ontario are part of the Credit River Valley Conservation Authority and are included in this study. With the exception of Cawthra Creek, Cooksville Creek and Sheridan Creek, all these watercourses are located below the Queen Elizabeth Way.

Most of the watershed is located in Peel County but small parts of Dufferin, Halton and Wellington Counties are also included. Member municipalities are:

- Regional Municipality of Halton,
  - Town of Oakville,
  - Town of Halton Hills,
- Regional Municipality of Peel,
  - City of Brampton,
  - City of Mississauga,
  - Town of Caledon,
- Town of Orangeville,
- Township of Erin,
- Village of Erin,
- Township of Amaranth,
- Township of East Garafraxa, and
- Township of Mono.

TOPOGRAPHY

The topography of the Credit River watershed is a direct result of the deposition and erosion processes during glacial and post-glacial times. Land surface elevations vary from 75 m above mean sea level at Lake Ontario to about 525 m in the extreme upper parts of the watershed.

The Niagara Escarpment cuts diagonally across the watershed in approximately a south-north direction. The Escarpment is characterized by a sharp topographic break, formed by cliffs of erosion resistant dolostone overlying softer shale. The Escarpment enters the watershed at a point to the southeast of Acton at an

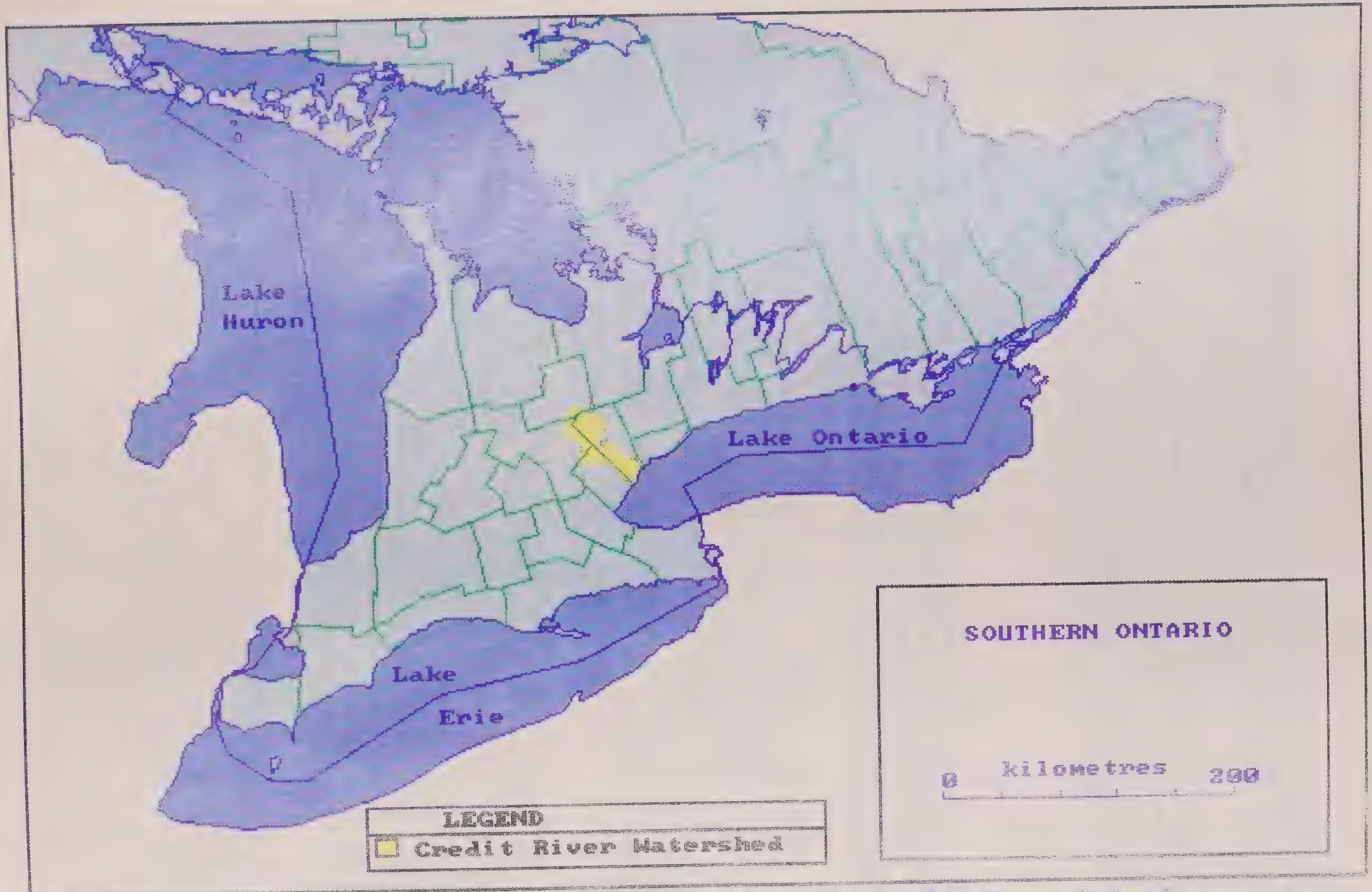


Figure 1. Location of the Credit River Watershed in Southern Ontario

elevation of approximately 340 m. From that point to Credit Forks, it stands out boldly overlooking a lower till plain to the southeast. Beyond Credit Forks, the Escarpment is almost completely hidden by hummocky morainic deposits.

Much of the area above the Escarpment is covered by moraines which produced a dissected, rugged to hilly landscape with a few drumlins intermingled with the moraines; while the other areas are of more gentle relief on till plains and meltwater channels. Below the Escarpment, a gently sloping area extends in a southeasterly direction towards Lake Ontario.

PHYSIOGRAPHY

The present landforms within the Credit River watershed are almost entirely the result of the last Wisconsinan glaciation of the ice age. Most of the land features are the result of material dumped by the ice or by meltwater as the ice advanced and retreated. Thus, the present physiography of the watershed closely corresponds with its Pleistocene geology.

According to Chapman and Putnam (1951), parts of eight major physiographic regions are found in the study area. These physiographic regions are: the Lake Iroquois Plain, the South Slope, the Peel Lake Plain, the Niagara Escarpment, the Oak Ridges Moraine, the Horseshoe Moraines, the Guelph Drumlin Field, and the Hillsburg Sandhills. Figure 2 shows the various physiographic regions in the watershed and constitutes an interpretation of Chapman and Putnam's ideas. Some of the boundaries between the various physiographic regions that are shown on Figure 2 are, therefore, approximate and at times arbitrary.

In the following text, the term moraine will be used to describe a topographic expression of material deposited at the edge of an ice sheet. Moraines that have been deposited along the margin of one ice lobe are referred to as end moraines. The term interlobate moraine refers to a moraine that was built between two ice lobes. Moraines are made either of till that has been deposited by a glacier, or of coarsely stratified gravel and sand that was deposited at the ice front by water issuing from the melting ice. A common trait of all moraines is a knobby surface with undrained depressions of irregular shape between the knobs, resulting from the melting of buried blocks of ice.

A level to very gently undulating surface underlain by till is referred to as a till plain. Local relief in a till plain is usually restricted to a few metres. Drumlins are low, oval-shaped hills, consisting of till, built under the margin of the ice, and shaped by its flow. Drumlins are of interest because their long axes are parallel to the direction of ice movement.

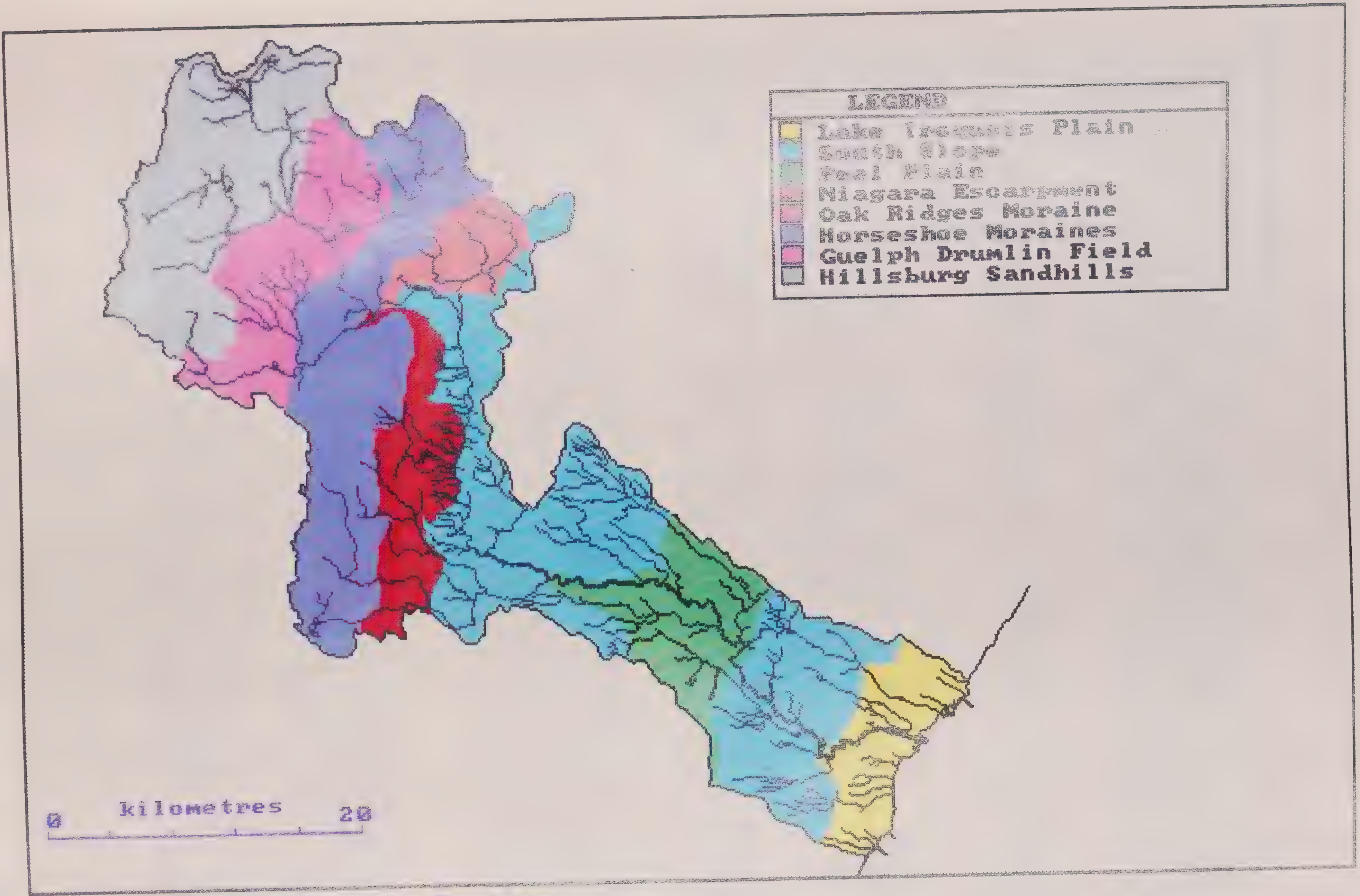


Figure 2. Physiographic Regions

The Lake Iroquois Plain

After the retreat of the last glacier, the Lake Ontario basin was occupied by a glacial lake, Lake Iroquois, which reached higher levels than Lake Ontario. The abandoned Lake Iroquois shoreline lies from 3 to 5 km north of the present-day shoreline of Lake Ontario and its elevation is about 115 m. Sand and gravel bars and beach terraces, 3 to 6 m high, are well displayed at surface along the abandoned shoreline.

The Lake Iroquois Plain slopes down towards Lake Ontario with an average slope of about 10 m per km. For the most part, the plain is covered with a thin sheet, less than 1 m in thickness, of sand and silty sand.

The South Slope

Within the Credit River watershed, the South Slope physiographic region is divided into a northern portion that drapes the base of the Niagara Escarpment and extends south to Highway 7; and a southern portion that extends from the Trafalgar Moraine to the Lake Iroquois shoreline.

Part of Palgrave Moraine, a strip of hummocky topography at the extreme northeastern corner of the watershed, and Cheltenham Moraine, a ridge of stratified sand extending to the south of Cheltenham, are included in the northern portion of the South Slope.

The southern portion of the South Slope includes the Trafalgar Moraine, a ridge extending from the headwaters of Loyalist Creek in the west to the headwaters of Cooksville Creek in the east. The relief of the Moraine is subdued to the east of Streetsville but quite definite to the west of it. Excluding the narrow strip of the Trafalgar Moraine, the topographic gradient of this portion of the South Slope is gentle and in the order of 6 m per km.

The Peel Plain

Lake Peel or Peel Ponding is the name given to a body of water, which was impounded between a lobe of ice projecting up the Humber River Valley and the high ground to the north, east, and west. The water level in Lake Peel seems to have been continuously falling, As a result, there are no major shoreline features (White, 1975).

As described by Chapman and Putnam (1951), the Peel Plain is a level to undulating tract of clay soils that cover the central portions of Halton, Peel, and York Counties. Across this plain, the Credit, Humber, Don, and Rouge Rivers have cut deep valleys, as have other streams such as the Bronte, Oakville, and Etobicoke Creeks.

Within the Credit River watershed, the Peel Plain is bounded by the South Slope physiographic region from the north and the south. The underlying geological material of the plain is till. In much of the Peel Plain, however, this has been modified by a thin veneer of clay and silt. An area located just to the south Highway 7 and extending in a southeasterly direction to Churchville appears to be a delta that was formed at an early stage of Lake Peel within a bedrock depression. The glacio-lacustrine deposits in this area consist of stratified sand and silt

Niagara Escarpment

As observed by Chapman and Putnam (1951), the Niagara Escarpment is by far the greatest topographic break produced by differential erosion of harder and softer rock in Ontario. Vertical cliffs along the brow outline the dolostone of the Cataract Group and Amable Formation while the slopes below are carved in red shale of the Queenston Formation.

The Niagara Escarpment enters the study area at a point to the southeast of Acton where the elevation is approximately 340 m. From that point, the Escarpment stands out boldly until it reaches Credit Forks. From Credit Forks northward to the watershed divide, the Escarpment is almost completely hidden by hummocky, morainic deposits.

The Oak Ridges Moraine

The Oak Ridges Moraine is one of the most distinctive physiographic regions in Southern Ontario. It extends from the Niagara Escarpment to the Trent River. The extreme western end of this physiographic region is located within the Credit River watershed, extending from Credit Forks in a northeasterly direction towards the watershed divide. The Moraine forms the Caledon and Albion Hills. It is characterized by a hilly topography with a knob-and-basin relief and surface elevations ranging from 300 to 350 m.

Horseshoe Moraines

A belt of moraines, composed mainly of till, extends from Acton in the south, flanks Caledon Village from the east, and continues to Orangeville in the north. The belt includes the Galt, Paris and Singhampton moraines and is part of a larger physiographic region known as the Horseshoe Moraines. From Singhampton to Caledon Village, the moraines lie along the brow and slopes of the Niagara Escarpment.

Within the Credit River watershed, the Galt Moraine is a rugged ridge of till that occupies a small area near Acton. The Paris Moraine, on the hand, is a high till ridge that crosses the watershed from south to north. An examination of the bedrock topography map reveals the existence of a bedrock high under the

Moraine (see Section: Bedrock Topography). The Paris Moraine extends from Acton in the south to Credit Forks in a southwest-northeast direction and forms a local water divide 400 to 420 m high. The crest of the ridge is hummocky with local relief exceeding 8 m. The Credit River valley cuts through the Moraine at Credit Fork. From there, the Moraine continues in a northeasterly direction towards the watershed divide again forming a local surface water divide 420 to 440 m high.

A broad meltwater channel consisting of gravel terraces was formed at the northwestern edge of the Paris Moraine and can be traced from Caledon Village to Brantford outside the watershed. The channel is associated with the running water that drained the ice front. In addition, outwash materials were deposited in the valleys of the Black and Silver Creeks by meltwater channels that drained the southeastern part of the Moraine.

The Singhampton Moraine is a single-crested till ridge of hummocky relief located to the northeast of Caledon and extending to the watershed divide at elevations between 440 to 460 m. Glacial drainage that flowed south of the Moraine to Orangeville and down to the path of the Credit River to Cataract laid down outwash sand and gravel beds.

Guelph Drumlin Field

Chapman and Putnam (1951) described the area located between the Paris Moraine to the east, the Singhampton Moraine to the north, and the Orangeville Moraine to the west as part of the Guelph Drumlin Field physiographic region. The field consists of low rolling, streamlined drumlins separated from each other by numerous interconnecting meltwater channels. Surface elevations range from 400 to 460 m. The major axes of the drumlins are between 0.5 and 2 km in length and are oriented at approximately N45W. The minor axes are between 0.2 to 0.5 km long.

Hillsburg Sandhills

To the west of a line extending from Hillsburg in the south to Orangeville in the north lies a prominent topographic feature known as the Orangeville Moraine. Chapman and Putnam (1951) identified the Orangeville Moraine as part of the Hillsburg Sandhills physiographic region. The Moraine forms a nearly flat topped positive feature, which has been strongly dissected by fluvial erosion. Elevations range between 440 and 500 m with local reliefs up to 30 m.

DRAINAGE

The Credit River drainage system rises in a hilly plateau of moraines, gravel terraces, and swamps above the Niagara Escarpment

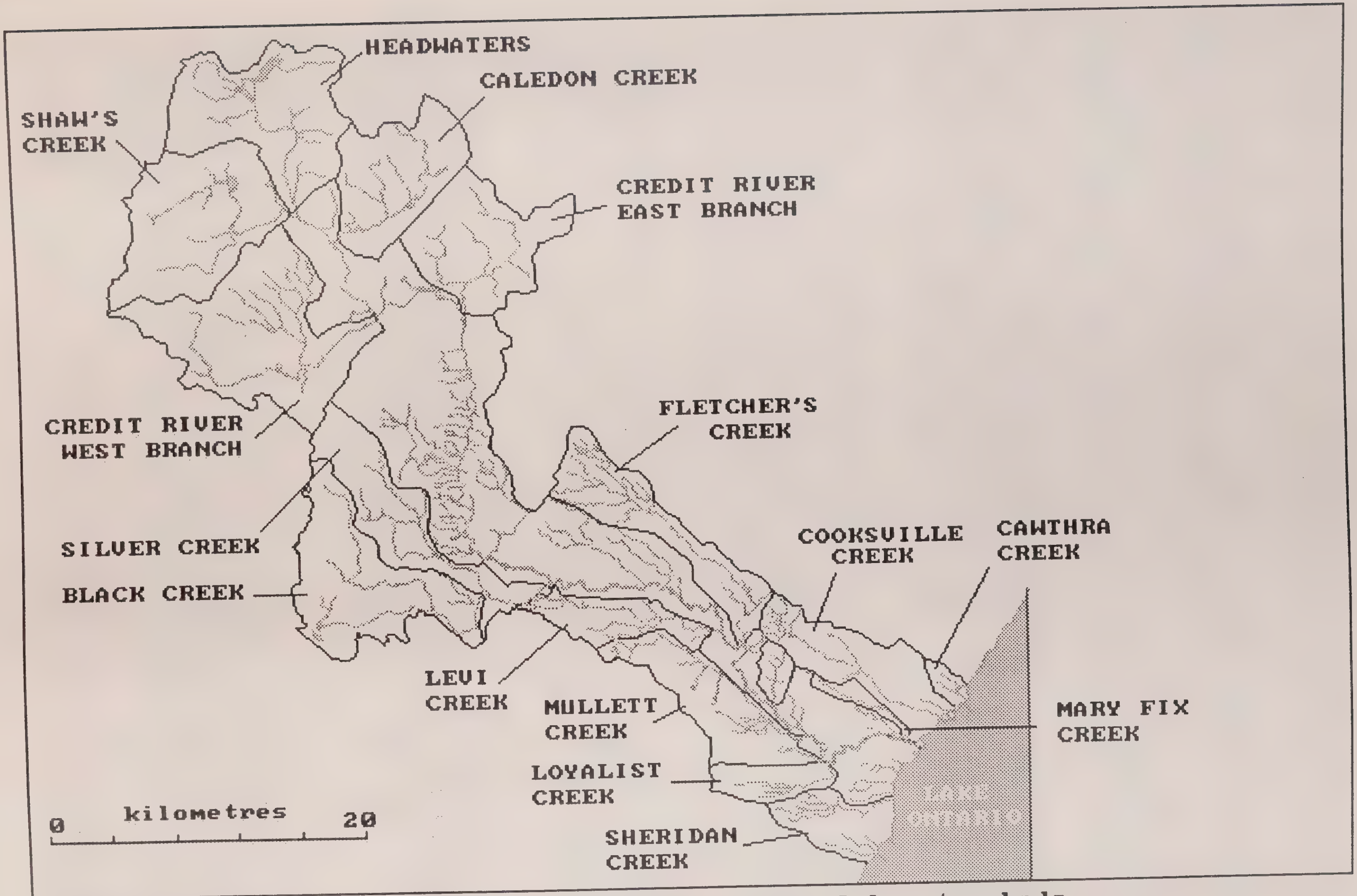


Figure 3. The Credit River Watershed and Major Sub-watersheds

at elevations between 415 to 480 m, and it empties into Lake Ontario at Port Credit for a total relief of about 400 m and a total length of about 90 km (Figure 3).

The Credit River system consists of two branches, the Credit River in the Orangeville-Alton-Cataract area and the West Credit River in the Hillsburgh-Erin-Belfountain area. Both rivers occupy abandoned meltwater channels containing numerous swamps areas.

The Credit River leaves the plateau through a deep notch in the Niagara Escarpment at Cataract while the west branch descends through a similar notch at Belfountain and joins the Credit River at Credit Forks east of Belfountain. Above the Escarpment, both branches have low gradients (3-5 m per km). As they flow over the Escarpment, however, their gradients increase to about 20 m per km.

Downstream from Credit Forks, the Credit river has built a wide alluvial plain and is joined by the East Credit River at Inglewood. From Inglewood, the river flows for about 16 km to the vicinity of Glen Williams in a narrow valley between the Escarpment and the till plain. Numerous, small, rapid feeders enter this portion of the Credit from the face of the Escarpment. They are actively eroding the shaley slope of the Escarpment and in a few places gullying has proceeded so far as to produce veritable badlands.

At Glen Williams, the river swings in a southeasterly direction and follows the slope of the till plain toward Lake Ontario with a gradient of about 4 m per km. The Black Creek and Silver Creek join together in Georgetown and then join the Credit River at Norval. From this point to Port Credit on Lake Ontario, the river valley cuts through a clay till plain and often into the underlying shale.

At Meadowvale South, Fletcher's Creek joins the Credit River. Then the river proceeds in a southerly direction to Erindale where the level of glacial Lake Iroquois occurs. The river cuts through a well-developed terrace into the shale and then is deflected northward by a barrier beach. The last 2 km of the river before entering Lake Ontario are drowned and marshy.

CLIMATE

The climate of the Credit River watershed is characterized by moderate winters, warm summers, and a long growing season with usually reliable rainfall. The local variations in climate reflect variations in topography, the proximity to Lake Ontario, and also the prevailing winds. The annual variations are dependent on the nature and frequency of the weather systems that cross the watershed.

Four meteorological stations are located within the Credit River

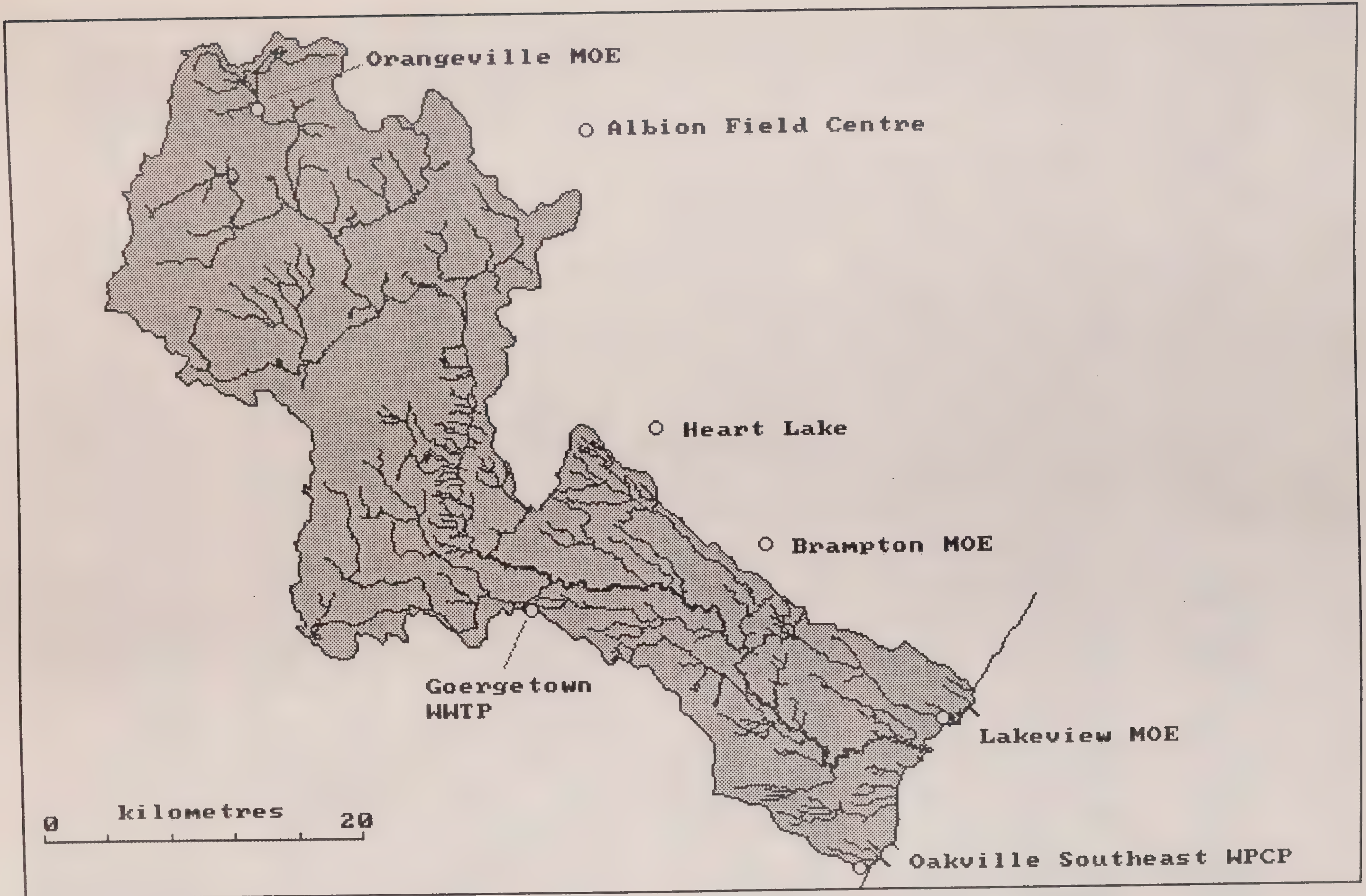


Figure 4. Location of Meteorological Stations in and around the Credit River Watershed

watershed, namely, Georgetown WWTP, Lakeview MOE, Oakville Southeast WPCP, and Orangeville MOE. In addition, four stations are located outside the watershed along its eastern boundary. These stations are: Albion Field Centre, Brampton MOE, Heart Lake, and Pearson International Airport (Figure 4).

Climatic data including temperature and precipitation since 1975 are available, with some gaps, for all the above stations. Table 1 gives the names of the stations and their periods of record. Table 2 provides a statistical summary of extreme values and Tables 3 and 4 give the monthly, annual and 15-year (1975-1989) means of precipitation and temperature data for the stations.

Brown et al (1968) published a map showing the climatic regions of Southern Ontario, which is reproduced in Figure 5. According to Brown et al, the Credit River watershed lies within five climatic regions: Lake Erie Counties, South Slopes, Huron Slopes, Simcoe And Kawartha Lakes, and Dundalk Upland.

Within the study area, the Lake Erie Counties climatic region consists of a narrow strip that is 5 to 6 km wide along Lake Ontario. The region is strongly influenced by the effects of Lake Ontario, which markedly lengthens the frost-free period in the fall and reduces early high daytime temperatures in the spring. Based on data measured at Lakeview MOE and Oakville Southeast WPCP meteorological stations, the 15-year mean annual temperature is 8 $^{\circ}$C and the 15-year mean annual precipitation is 789 mm.

The South Slopes climatic region extends from roughly Highway 5 in Mississauga northwards to the Niagara Escarpment and Caledon-Albion Hills. Brampton MOE, Georgetown WWTP, Pearson International Airport, and Heart Lake meteorological stations typify the South Slopes climatic region. The southern parts of the region are influenced to a certain extent by Lake Ontario, but this influence is insignificant beyond 30 km from the lake shore. The 15-year mean annual temperature is 7.6 $^{\circ}$C, and the 15-year mean annual precipitation is 812 mm.

Within the Credit River watershed, the area above Terra Cotta and Inglewood, and including the Belfountain area, lies in the extreme eastern part of the Huron Slopes climatic region. Largely because of its elevation, the region has somewhat lower temperatures and more snow. The 15-year mean annual temperature is 6.3 $^{\circ}$C, and the 15-year mean annual precipitation is 807 mm (Albion Field Centre meteorological station).

Most of northern Peel lies within the Simcoe and Kawartha Lakes climatic region. The former village of Caledon lies in this region. No data are available for this climatic region within the watershed. Generally, annual and seasonal temperatures are similar to those of the Huron Slopes.

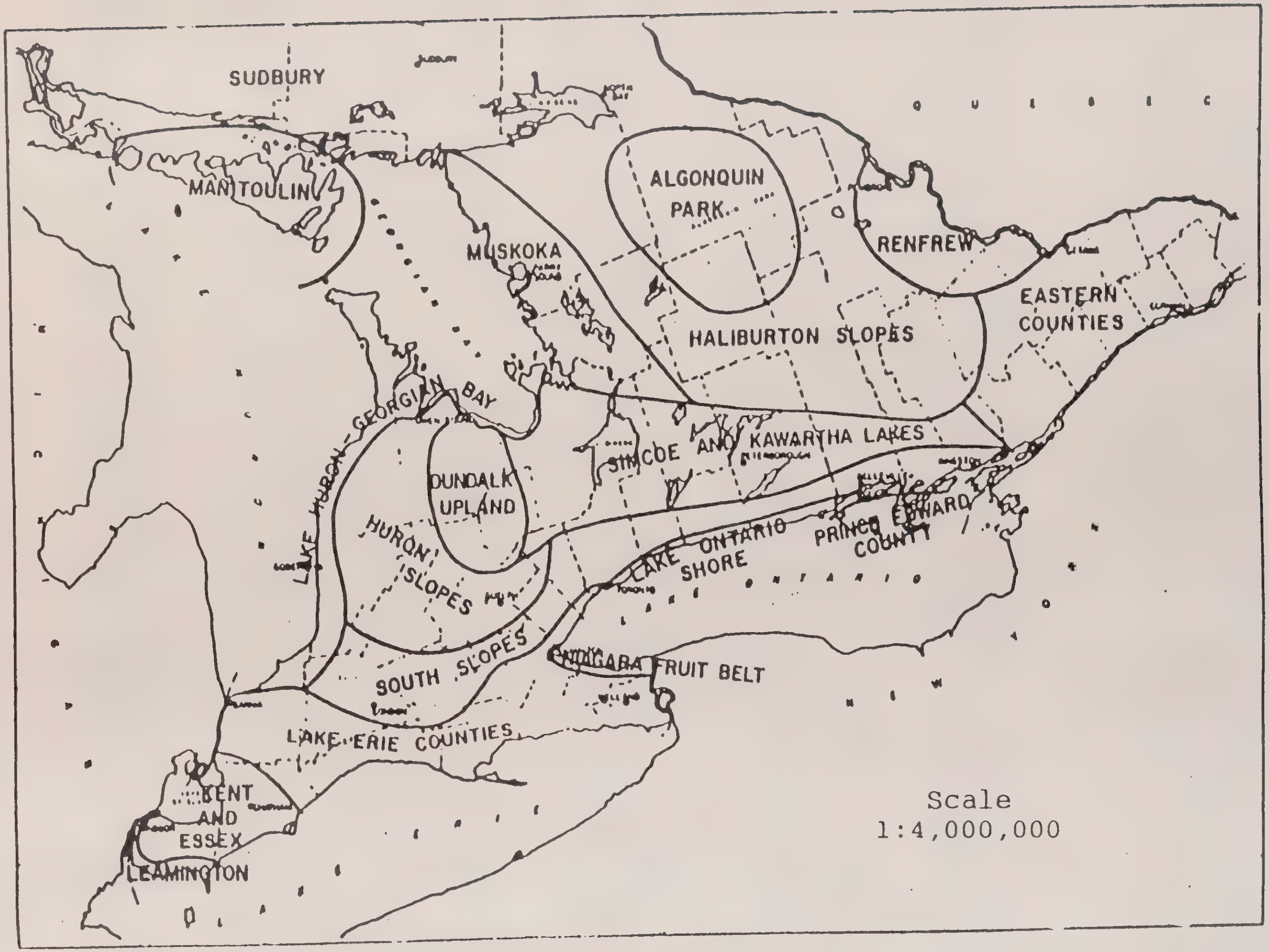


Figure 5. Climatic Regions Of Southern Ontario (after Brown et al,1968)

The extreme northwestern part of the Credit River watershed, including Orangeville, lies within the Dundalk Uplands climatic region. This region has the most severe climate in southwestern Ontario, comparable to areas further north and northeast in the province. Nevertheless, the climate is still "moderate" by overall Canadian standards. The 15-year mean annual temperature is 5.8 ^{o}C, the 15-year mean annual precipitation is 898 mm.

SOILS

The soils of the Credit River watershed reflect the climate and geologic processes through which the area has undergone, and they have characteristics strongly related to those of the glacial or bedrock parent materials.

Soils are classified in terms of series, types and phases. The term soil series is used to designate a group of soils whose profiles are alike with regard to their general character and appearance and which were developed from similar parent materials. They are usually given a geographic name from a town, village, township, etc.

The term soil type is used to describe the textural composition of the soil (sand, loam, clay). Finally, the term soil phase refers to all the variations that occur in a soil series other than texture, such as stoniness, shallowness, topography, drainage and erosion.

Forty three classes of soils are present in the study area based on soil maps published by Hoffman and Richards (1953), Hoffman et al (1963, 1964), and Gillespie et al (1971). Five soil classes developed over shale and range in texture from clay to clay loam, 15 classes developed on glacial till and range in texture from clay loam to loam, 16 classes developed on outwash deposits and range in texture from sandy loam to sand, 5 classes developed on lacustrine deposits and range in texture from clay to silt loam. Finally, one class with a fine sandy loam texture developed on alluvium deposits, and one class has an organic origin and is made up of muck.

Table 5 gives the names and symbols of various soils found within the Credit River watershed and Table 6 gives their names, texture, parent material, natural drainage, topography, and stoniness.

GEOLOGY

BEDROCK GEOLOGY

The occurrence, flow, and quality of groundwater are strongly influenced by geology. Therefore, it is important in any groundwater investigation to have a full consideration of the characteristics of the geologic deposits within the area under study.

The consolidated bedrock in Southern Ontario consists of Palaeozoic sedimentary rocks of Devonian, Silurian, and Ordovician Age, resting on the Precambrian basement. These Palaeozoic rocks dip regionally to the southwest at about 5 metres to the kilometre. The oldest rocks of Precambrian Age outcrop in the northeastern parts of Ontario while the younger rocks of Devonian Age outcrop in the southwestern parts.

An unconformity is defined a surface separating an overlying younger rock formation from an underlying older formation. It represents a period of erosion or no deposition. Several regional unconformities exist in Ontario between Precambrian-Ordovician, Ordovician-Silurian, and Silurian-Quaternary rocks.

In much of Southern Ontario, glacial (overburden) deposits obscure much of the Palaeozoic bedrock. In most places, the bedrock is moderately to deeply buried beneath the overburden, but there are areas where the overburden is not present and the bedrock is exposed at surface. Within the Credit River watershed, surface exposures of the bedrock are found near Erindale, at and near Streetsville, along the Credit River and its tributaries from Glen Williams to Huttonville, in the Terra Cotta area, along the face of the Niagara Escarpment, and at a few places above the Escarpment.

The Palaeozoic rocks within the Credit River watershed are divided into several units or formations. The oldest rocks are those of the Georgian Bay and Queenston Formations of the Upper Ordovician Age. The Queenston Formation is covered by rocks of the Cataract Group of the Lower Silurian Age. Overlying the Cataract Group, are the rocks of the Reynales-Fossil Hill Formation of the Clinton Group. This in turn is covered by the Amabel and Guelph Formations of the Middle Silurian Age (Map 2). The following are brief descriptions of these formations and groups.

Georgian Bay Formation

Rocks of the Georgian Bay Formation form the bedrock surface in the southern parts of the study area extending from Streetsville to Lake Ontario. The Georgian Bay Formation has a thickness of approximately 165 m. It consists of blue-grey shale with interbeds of siltstone, sandstone, and limestone. The upper part of the

Formation is somewhat more calcareous and less shaley than the lower part.

According to Liberty (1969), the rocks of the Georgian Bay Formation were deposited in a shallow sea as indicated by ripple marks, the abundance of fauna and the absence of coarse clastic rocks. Deepening sea conditions and a facies shift is indicated by the increasing dominance of limestone in the upper parts of the formation.

Queenston Formation

Conformably overlying the Georgian Bay Formation is the Queenston Formation. It underlies a large area within the watershed extending from Streetsville to the base of the Niagara Escarpment. The Formation is Upper Ordovician in age and is 135 to 150 m thick in the Terra Cotta area, but thins somewhat northwards (Hewitt, 1969).

Liberty (1969) suggests that the Queenston shales were deposited as shallow-water sediments, whose iron content was subsequently oxidized during deposition or shortly after. The Formation consists of unfossiliferous, thin to thick bedded, brick-red shales. In places, the brick-red shales are seemed by narrow greenish bands along vertical, small joint fissures and also parallel to the bedding planes. The rocks readily weather to a red clay soil.

Cataract Group

Unconformably overlying the Queenston Formation, is the Cataract Group of the Lower Silurian Age. The Cataract Group consists of three formations: Whirlpool, Manitoulin, and Cabot Head. The Whirlpool Formation is unfossiliferous and outcrops along the base of the Niagara Escarpment. The Whirlpool Formation is about 5 m thick at Cataract (Caley, 1940) and consists of thin- to massive-bedded, grey to reddish-coloured sandstone.

Overlying the Whirlpool sandstone is the Manitoulin Formation. It occurs along the West Credit River north of Belfountain, in the Cataract-Credit Forks area, and in the Orangeville area. The Formation is 5 m thick and consists of fossiliferous, thick- to medium-bedded dolomite with shale partings and lenses of white chert. Bolton (1957) suggested that the Manitoulin Formation was deposited in a shallow, warm, well-aerated sea.

The Cabot Head Formation is about 10 m thick and outcrops sparingly in the face of the Niagara Escarpment. It consists of thinly-bedded, grey-green shale with thin interbeds of grey and rust-coloured calcareous sandstone and limestone. The Formation is fossiliferous. Bolton (1957) proposed that the Formation was deposited in a shallow, marine environment.

Clinton Group

Overlying the Cataract Group is the Clinton Group of Middle Silurian Age. Within the Credit River watershed, the Reynales-Fossil Hill Formation of the Clinton Group is sparsely exposed in the Niagara Escarpment. It is a dolomite 2 to 2.5 m thick, which grades northwards from a grey, medium-bedded, fine argillaceous dolomite to a brown, crystalline dolomite rich in fossil.

Amabel Formation

The Amabel Formation of the Middle Silurian Age forms the cap rock of the Niagara Escarpment. It is light-grey, medium to coarsely crystalline, generally massive-bedded dolomite. The Formation has reef structures and is highly fossiliferous. According to Bolton (1957), the Formation was deposited in a stable sea shelf environment.

Although the maximum thickness exposed in the Niagara Escarpment is about 8 m at Credit Forks, the total thickness of the Formation is probably greater than 30 m. The Formation contains solution cavities and it is highly fractured.

Guelph Formation

The Guelph Formation of Middle Silurian Age rests on top of the Amabel Formation in the area of East Garafraxa at the extreme western part of the Credit River watershed. It consists of light-brown, medium to massive-bedded, uniformly textured, reefy dolomite. In well cuttings, the rocks of the Guelph Formation are not distinct from those of the Amabel Formation. This indicates that the contact between the two Formations is gradational. Because of their similar composition, both Formations act as one hydrogeologic unit. Their combined thickness ranges from 45 to 120 m.

BEDROCK TOPOGRAPHY

Chapman and Putnam, 1951 noted that before the advent of the glacial periods, the Palaeozoic rock had been subjected to erosional processes for about 250 million years. The surfaces of the more easily eroded rocks, such as shales, were lowered, leaving the harder dolostone or limestone to form uplands. By far the greatest topographic break produced by differential erosion of harder and softer rock in Ontario is the Niagara Escarpment.

The bedrock topography in the Credit River watershed is shown on Figure 6 and Map 3. Records of water wells that penetrated the overburden to the bedrock and the elevations of bedrock exposures were used to construct the bedrock elevation distribution.

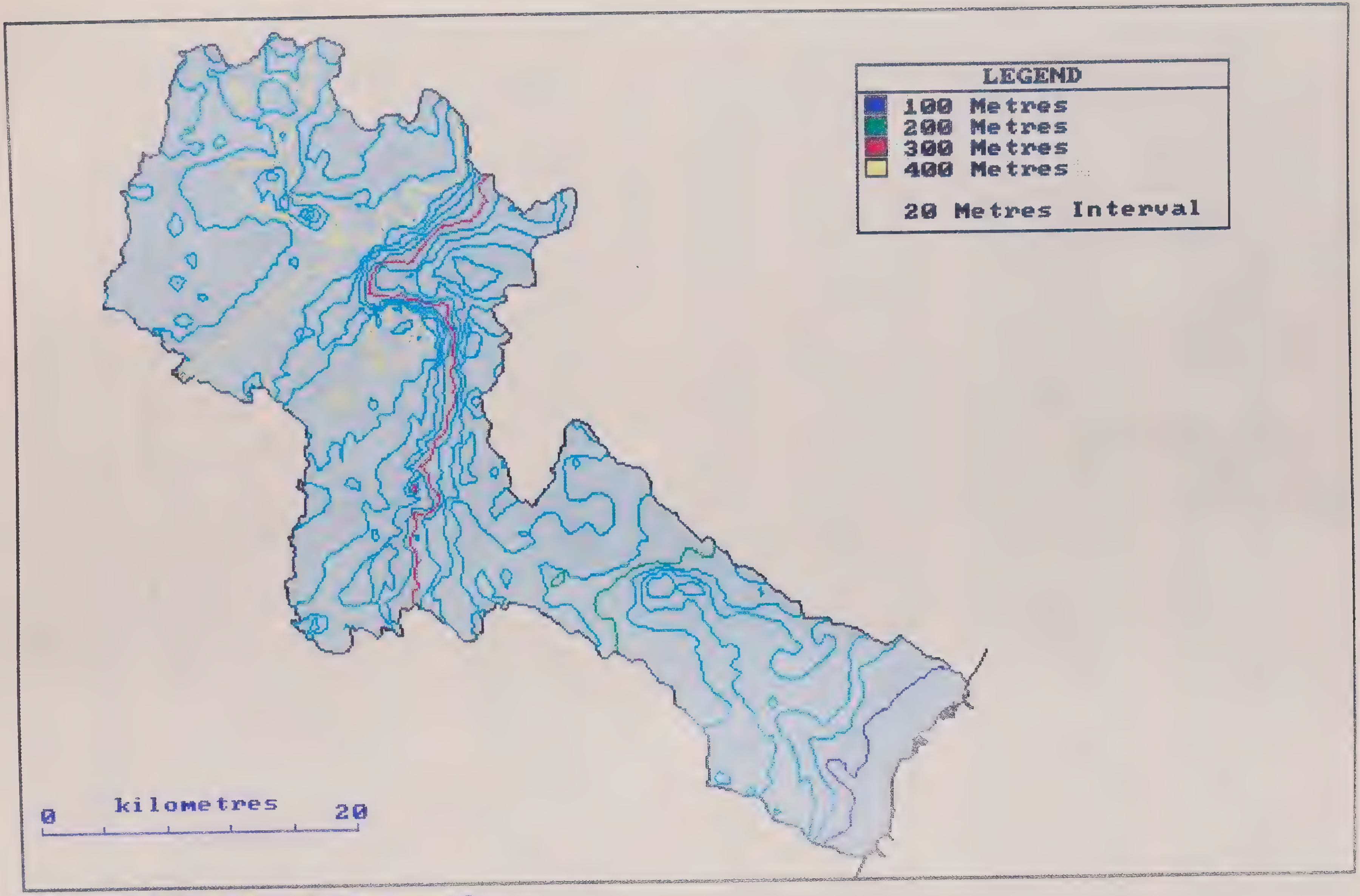


Figure 6. Bedrock Topography

The bedrock topography is similar to present-day topographic surface. Highest bedrock elevations (440- 460 m) are found along the watershed topographic divide in the townships of Erin, Garafraxa, and Amaranth. From these highs, the bedrock surface forms a plateau, which slopes towards the well defined Niagara Escarpment.

Drainage patterns within the bedrock surface above the Escarpment resemble to a great degree present-day drainage patterns. Local bedrock topographic divides seem to coincide with present-day divides and three bedrock valleys appear to have been well established. One valley extends from Orangeville down the current Credit River valley to the Escarpment, the second extends along the current Shaw's Creek valley, and the third extends from Erin to Belfountain.

Below the Escarpment, the bedrock surface slopes gently towards Lake Ontario. From Credit Fork to Cheltenham, a bedrock valley appears to be slightly to the north and east of the present-day Credit River valley. From Cheltenham to Port Credit, the bedrock valley appears to follow closely the present-day Credit River Valley.

A bedrock depression appears to exist below Highway 7 and extends south to Churchville. Sand, and silty sand of glacio-lacustrine origin outcrop at surface where the depression occurs.

PLEISTOCENE GEOLOGY

The unconsolidated materials overlying the bedrock in the Credit River watershed were deposited during the Pleistocene or Glacial Epoch and are considered of the late Wisconsin ice advance, which retreated some 12,000 years ago. The watershed may have been overrun by several pre-Wisconsin ice movements. If so, the Wisconsin ice advance has obliterated evidence of any former glaciations.

During the Wisconsin glaciation, the ice flowed from the northwest (Georgian Bay ice lobe), the northeast (Lake Simcoe ice lobe) and the east and southeast (Lake Ontario ice lobe). The ice laid down till plains. Drumlins were formed under the ice and they occur as isolated hills on the till plains. As the ice retreated, pauses or possible slight readvances deposited the Singhampton, Paris, and later the Galt moraines. Meltwater flowed and formed spillways (meltwater channels), parts of which are now occupied by the Credit River drainage system. As the ice retreated, outwash plains, and terraces were deposited by the sediment laden waters flowing off the ice masses. All these deposits are present in the watershed and are discussed below (Figure 7 and Map 4).

Data from bedrock wells and elevations of bedrock exposures were

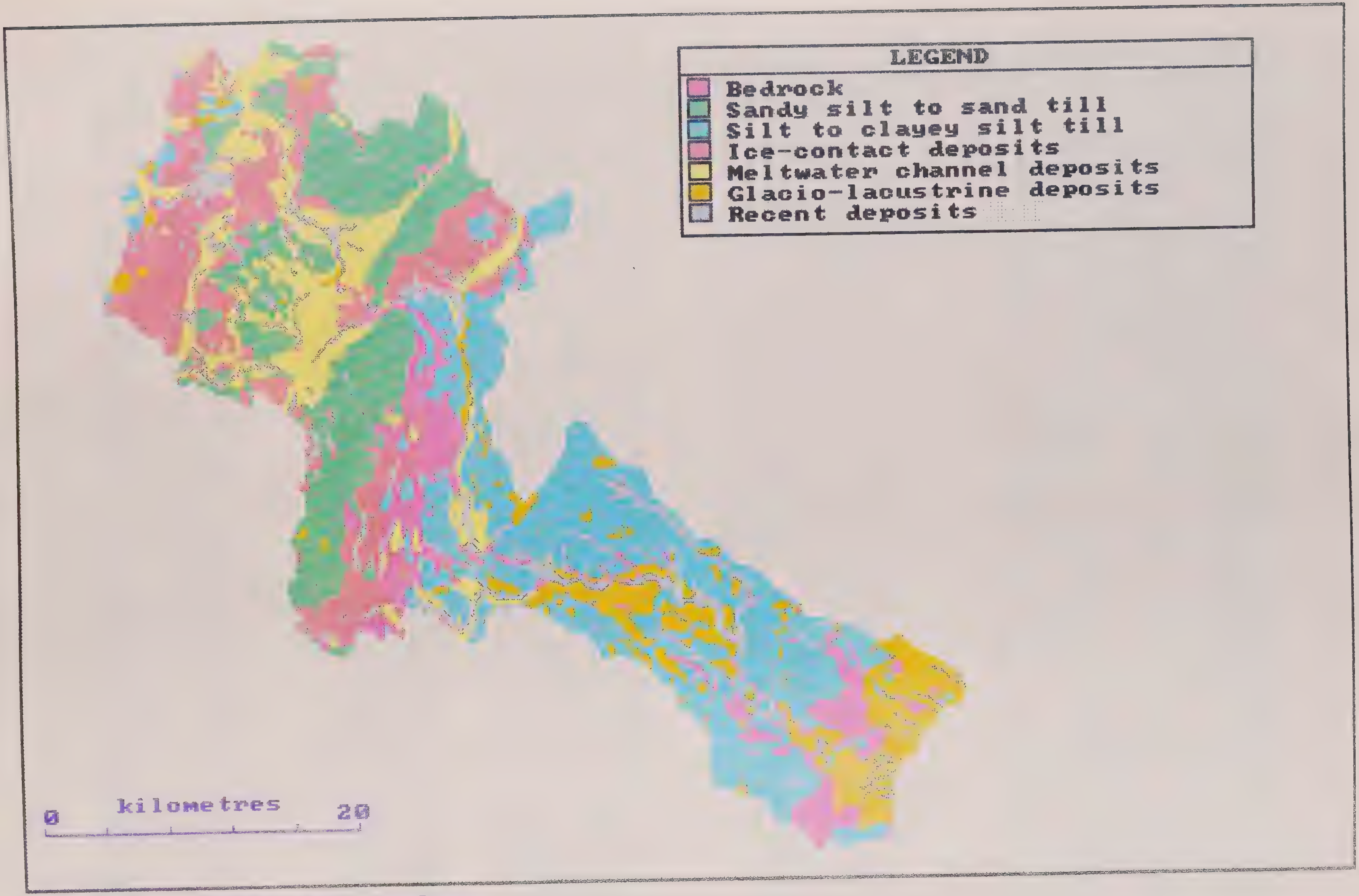


Figure 7. Surficial Geology

used to construct the overburden thickness within the watershed (Figure 8 and Map 5). At the base of the Escarpment and in the lower parts of the watershed, the overburden thickness is less than one metre. Most of the area below the Escarpment, however, has an overburden thickness ranging from 10 to 20 m and can reach 50 m in some places. Above the Escarpment, the thickness of the overburden within the Orangeville, the Oak Ridges, and the lower parts of the Paris Moraines ranges from 40 to 50 m. The thickness of the overburden within the Singhampton Moraine is between 10 and 30 m and reaches 50 m in a small area. The thickness of the overburden in the areas between the Moraines ranges from 20 to 30 m. At a few places, where the bedrock is close to surface, the thickness of the overburden is limited ranging from less than one metre to a few metres.

Glacial Deposits

Within the Credit River watershed, two types of till can be identified: a sandy silt to sand till and a silt to clayey silt till. Three sandy silt to sand tills occur in the watershed: the Newmarket Till, the Wentworth Till, and the Port Stanley Till. These tills have many similarities and it is difficult to subdivide them without good stratigraphic control or morphologic discontinuities. Two silt to clayey silt tills occur in the watershed: the Tavistock Till and the Halton Till.

Newmarket Till

Gwyn (1972), formally named this till after Newmarket where the till outcrops over a large area. Within the Credit River watershed, the till outcrops in Mono and Caledon townships within a belt of rolling to hummocky topography consisting largely of the Singhampton Moraine. The Newmarket Till represents an advance of the Lake Simcoe ice lobe from the northeast and the Singhampton Moraine marks the outer limit of the Newmarket Till within the study area (Cowan, 1976).

This is a brown to yellowish brown, sandy silt till containing numerous lenses of stratified drift. Its thicknesses is between 10 and 30 m. According to Cowan (1976), the lithology of the till appears to vary considerably. Generally, however, a significant percentage of materials from Ordovician rocks and from the Cataract Group are present.

Wentworth Till

This till was named after its type-area in Wentworth County. According to Cowan (1976), the Wentworth Till is the result of a glacial advance from the Lake Ontario basin.

Within the Credit River watershed, the Wentworth Till forms a belt of hummocky topography extending from Acton in the southwest to the

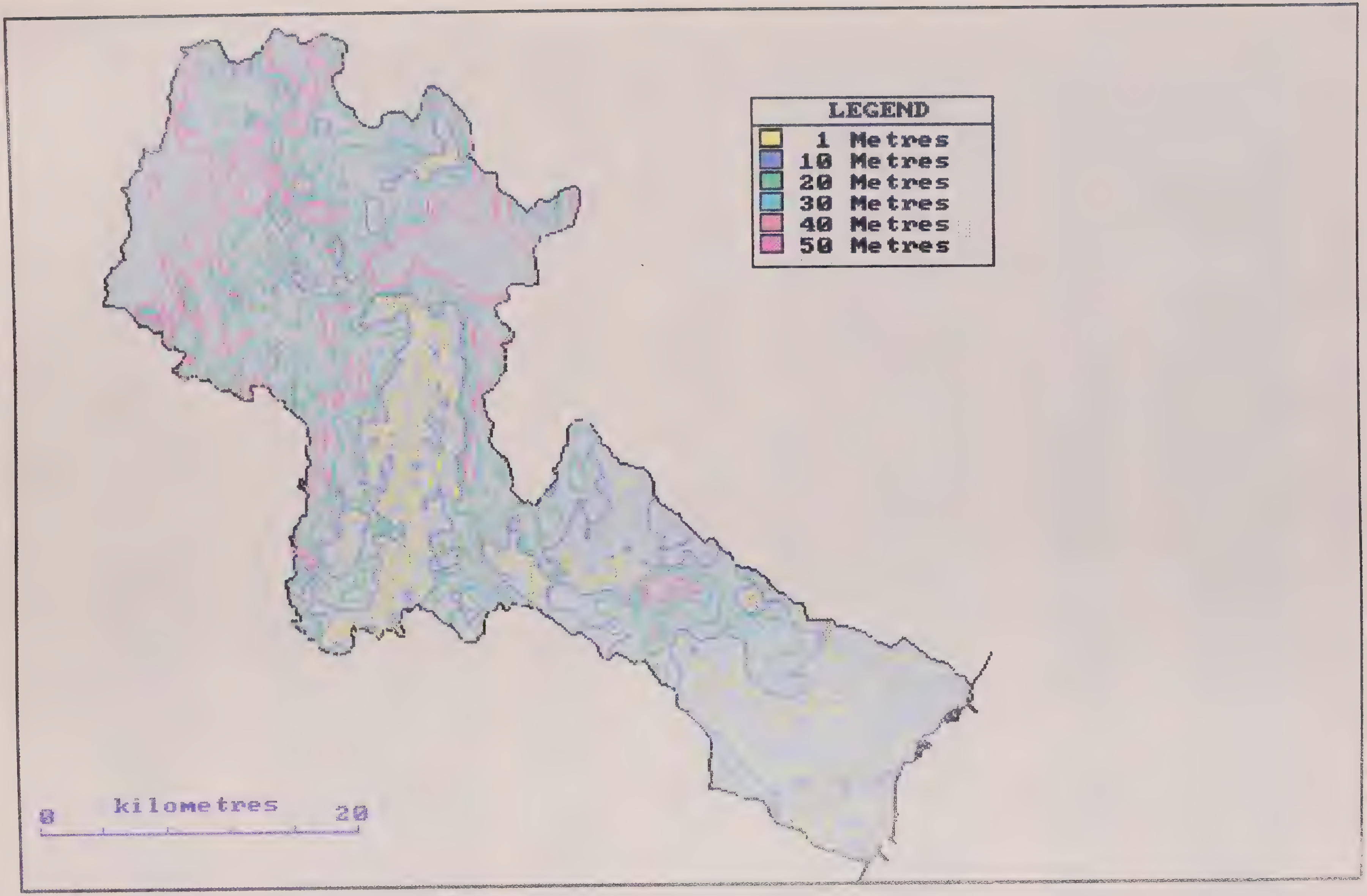


Figure 8. Overburden Thickness

headwaters of Caledon Creek in the northeast, and consists largely of the Paris and Galt Moraines. A few drumlins are associated with the till and are located on the eastern flank of the Paris Moraine in the Town of Caledon. The thickness of the till along the southern crest of the Paris Moraine ranges from 40 to 50 m. In the other areas it ranges from 10 to 30 m.

The Wentworth Till is generally a yellowish-brown, sandy to silty sand till, often containing stones or boulders (Karrow, 1968). Within the study area, the till becomes reddish in colour due to inclusion of the red coloured Queenston shale.

Port Stanley Till

The Port Stanley Till was deposited by an advance of the Lake Ontario ice lobe from the southeast (Cowan 1976). Within the study area, the Port Stanley Till occupies a broad track of rolling ground known as the Guelph Drumlin Field east of Orangeville Moraine in the townships of Erin and Caledon. It is yellowish-brown to light yellowish-brown, stony to bouldery sand silt till. Its thickness ranges from 10 to 30 m. The Port Stanley Till is texturally similar to the Wentworth and Newmarket tills though it is more dolomitic and has greater total carbonate content (Cowan, 1976).

Two silt to clayey silt tills have been identified in the Credit River watershed. These are the Tavistock Till and the Halton Till.

Tavistock Till

The Tavistock Till takes its name from the Village of Tavistock. It was previously mapped as the "Northern Till" in the Guelph area by Karrow (1968), and as Till "C" in the Conestogo area (Karrow 1971).

The Tavistock Till was laid down during a glacial advance of the Georgian Bay ice lobe (Terasmae et al 1972). Within the study area, the till flanks and overlies the western part of the Orangeville Moraine in the Townships of East Garafraxa and Amaranth and ranges from less than 1 m to 12 m in thickness. It is generally observed in an oxidized state with colours ranging from brown to dark yellowish-brown; the un-oxidized colour is dark grey or dark greyish-brown. The till is usually a silt or clayey silt, however, it is often more sandy where it overlies sand on the western flank of the Orangeville Moraine (Cowan, 1976).

Halton Till

The silt to clayey silt Halton Till covers a large area within the Credit River watershed. The till is considered to represent the last Wisconsinan ice advance out of the Lake Ontario basin. The Halton Till is present as a thin strip along the edge and over the

lower slopes of the Niagara Escarpment. It forms the Palgrave Moraine at the extreme northwestern corner of the watershed and the Trafalgar Moraine in the lower end of the watershed. The till also forms a gently rolling till plain extending from the lower slopes of the Niagara Escarpment to the abandoned Lake Iroquois shoreline. The till is either exposed at the surface or is concealed by a thin veneer cover of lacustrine deposits.

The Halton Till has a grey colour and weathers to a yellowish or reddish-brown colour in the oxidized zone. Its thickness ranges from 3 to 6 m and probably exceeds 15 m in the Palgrave Moraine area (White, 1975).

Glacio-fluvial Deposits

Two types of glacio-fluvial deposits are found in the Credit River watershed: ice-contact stratified drift and meltwater channel deposits.

Ice-contact stratified Drift

Most of these deposits are associated with the Orangeville and the Oak Ridges Moraines. The Orangeville Moraine is located in the extreme northwestern part of the watershed and extends from the Township of Mono in the northeast to Hillsburg in the Township of Erin in the southwest. The Moraine was formed between the Georgian Bay ice lobe at the west and northwest, the Lake Simcoe ice sub-lobe to the northeast, and the Lake Ontario ice lobe to the east and southeast

According to Chapman and Putnam (1951), the Orangeville Moraine is one of the first land form to appear in Southern Ontario when the Georgian Bay and Lake Ontario ice lobes separated. The Orangeville Moraine consists mainly of stratified sand, silt, and gravel. The bulk of the moraine exceeds 50 m in thickness.

In the northeastern parts of the Credit River watershed, deep beds of evenly graded fine sand occur between the Palgrave Moraine to the southeast and the Paris Moraine to northwest and extend from the watershed divide to Credit Forks. These sediments constitute the extreme western tip of the Oak Ridges Moraine, a major physiographic region in Southern Ontario extending from the Niagara Escarpment to the Trent River. Within the study area, the thickness of these deposits range from 40 to 50 m.

Meltwater Channel Deposits

These deposits of gravel and sand were laid down by old glacial meltwater channels associated with various ice lobes that covered the watershed. One channel is known as the Hillsburg channel (Cowan, 1976) and it extends from the south of Caledon Lakes to Hillsburg along the eastern limb of the Orangeville Moraine. The

martial is outwash gravel and may exceed 7 m in thickness.

Another channel was formed when the northeasterly limb of the Orangeville Moraine was breached to initiate drainage via the Credit River channel from Orangeville to Alton. Further ice retreat extended the Credit River channel to Cataract. The deposits vary from sand and silty gravel to clean uniform stratified gravel with a thickness ranging from less than 8 m to more than 15 m. The deposits are contiguous with the Caledon outwash deposits at Cataract.

A third channel, the Caledon Meltwater Channel (White, 1975), traverses the rim of the Escarpment from Sleswick outside the watershed past the Village of Caledon and then southwest past Cataract to Erin. The channel is a broad, shallow valley with a flat to gently undulating floor. The material is gravel covered by well sorted fine to medium sand. According to White (1976), these deposits were laid down as the Lake Ontario ice lobe stood at the Paris Moraine.

A fourth channel system occurs along the Black River and Silver Creek and extends to Georgetown. A fifth channel, known as the Caledon East Meltwater Channel (White, 1975), extends from the settlement of Albion outside the watershed to Inglewood. Below Inglewood, the channel disappears possibly beneath the present East Credit River until Terra Cotta where it appears again and continues to Glen Williams. The channel floor is relatively flat and is underlain by fine to medium sand.

At present, extraction from glacio-fluvial deposits is centred in Mono township, immediately northwest of Orangeville and in Erin Township near Hillsburgh. Gravel in the Hillsburgh meltwater channel is largely unexploited.

Glacio-lacustrine Deposits

Within the Credit River watershed, glacio-lacustrine deposits are associated with Lake Peel and Lake Iroquois. In addition, sediments indicating the presence of proglacial lakes or postglacial pondings occur in the Orangeville Moraine area, particularly in the southern part.

The Lake Peel sediments are found in the southern part of the watershed just to the north of the Trafalgar Moraine. They were laid down in a brief stand of water referred to as the Lake Peel Ponding. In general, the thickness of the deposits ranges from a few centimetres to less than a metre, and they consist of clay, silt and fine sand on top of the Halton Till. An area covered with deltaic deposits of fine and silt sand outcrop below Highway 7 and extend in a southeasterly direction to Churchville. These deposits may have been laid down at an early stage of Lake Peel.

The Lake Iroquois sediments were deposited along and to the south of the abandoned shoreline. For the most part, these deposits consist of sand and silt sand less than a metre thick. Sand and gravel bars and beach deposits are displayed at surface along the abandoned shoreline. A well developed terrace, forms a barrier at Erindale and forces the Credit River to deflect northward.

RECENT GEOLOGY

Along most of the main stream valleys there are terraces formed when the streams were flowing at higher levels. They are composed of a mixture of gravel, sand, silt and clay.

Tracts of poorly drained land containing organic materials occur in the meltwater channels and shallow depressions. Most of the material consist of black muck, though peat occurs in many places.

HYDROGEOLOGY

GENERAL PRINCIPLES AND DEFINITIONS

Subsurface waters occur in two zones below the land surface: the unsaturated zone and the saturated zone. The first zone extends from the land surface down to the water table and includes the capillary fringe. This zone contains liquid water under less than atmospheric pressure, and water vapour and air, or other gases, at atmospheric pressure. In parts of this zone, interstices, particularly the small ones, may be temporarily or permanently filled with water. The second zone (i.e. the saturated zone) is that zone in which all voids, large and small, are filled with water under pressure greater than atmospheric (Lohman, 1972). The top boundary of the saturated zone, at which pressure is atmospheric, is called the water table.

Groundwater is that part of the subsurface water, which occurs in the zone of saturation and is subject to continuous movement. The geometry and intensity of groundwater flow are dependent on the hydrologic environment consisting of topography, climate, and geology (To'th, 1972). The source of and recharge to groundwater comes from precipitation, directly by infiltration from the land surface or indirectly by surface water leaking from streams, ditches or ponds. The land surface topography exerts a controlling influence upon the configuration of the water table, the distribution of flow systems, and consequently groundwater movement. The occurrence, movement, quality and availability of groundwater also depends on geologic factors, in particular, lithology, porosity, permeability, and the areal distribution of various deposits.

An aquifer is a geologic formation capable of storing and transmitting a large quantity of water. Aquifers vary in thickness and areal extent. Some aquifers are small and may only be able to supply water to one or a few households. Others are large ranging in size from a few hectares to hundreds of square kilometres. Aquifers may be found in bedrock and in the overburden (unconsolidated materials) overlying the bedrock. The more fractures and openings there are in the bedrock the higher the water yield of the aquifer. In the overburden, aquifers consist of sand and/or gravel. Coarse sand and gravel constitute good aquifers while fine sand and silt are indicative of poor aquifers.

A geologic formation that is saturated but has low permeability and, therefore, does not furnish an adequate supply of water is called an aquiclude. Examples of aquiclude are clay formations or poorly-fractured rock formations with a few interconnected pore spaces. An aquifuge is an impermeable formation neither containing nor transmitting water; solid granite belongs in this category.

An aquifer that is overlain by a confining layer that has low permeability is called an artesian or confined aquifer. Groundwater in wells drilled in confined aquifers rises above the point where the water is found and sometimes flow over the ground surface.

Groundwater occurs in the openings within the aquifer. These openings may be in the form of pore spaces between grains of silt, sand or gravel, or in the form of solution cavities, fissures, joints, and bedding planes. The ratio of the volume of the pore spaces to the total volume of the water bearing material is called porosity.

In unconsolidated deposits, porosity is controlled by the shape, arrangement, degree of sorting, and cementation of particles. Porosity is high in well sorted deposits and low in poorly sorted and highly cemented deposits. In consolidated rocks, porosity is dependent on the extent of cementation and the degree of development of the fissure system or the solution cavity openings. Effective porosity refers to the amount of interconnected pore spaces or other openings available for water transmission.

Porosity is not a measure of the amount of water that an aquifer will ultimately yield. The ratio of the volume of water which the rock, after being saturated, will yield by gravity drainage to the volume of the rock is called the specific yield. The specific retention is the complement of the specific yield. It is the ratio of the volume of the water which the rock, after being saturated, will retain against the force of gravity to the volume of the rock.

The storage coefficient is the volume of water an aquifer releases from or takes in storage, per unit surface area of the aquifer, per unit change in head. In an unconfined aquifer, the storage coefficient is virtually equal to the specific yield. However, in a confined aquifer, it is less than the specific yield as the water derived from storage comes from expansion of the water and compression of the aquifer. Similarly, water added to storage is accommodated by compression of the water and expansion of the aquifer (Lohman, 1972).

Ground water flow occurs under a hydraulic gradient which is defined as the change in static head per unit of distance along the ground water flow path. The relative ease with which a water bearing material can transmit water under a hydraulic gradient is a measure of the permeability or hydraulic conductivity of the material, and is a measure of the capacity of a material to transmit water.

Transmissivity is the rate at which water at the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient, and is equal to the product of the hydraulic conductivity of the aquifer and its

thickness.

The specific capacity of a well is defined as its yield per unit of drawdown, expressed as litres per minute per metre of drawdown (L/min/m). Dividing the yield of a well by the drawdown for a specific time during a pump test, gives the value of specific capacity.

The specific capacity of a well is a function of the type of the aquifer, well diameter, pumping time, partial penetration, hydrogeologic boundaries, and well construction characteristics. Because of the above-mentioned constraints, the specific capacity is not an exact criterion with which to calculate the transmissivity, however, it is a useful index to describe the water yielding characteristics of the well and of the formation the well taps. In general, high specific capacities are indicative of high transmissivities and, consequently, high water yielding capacities.

In applied hydrogeology, pumping and recovery tests of wells generally give the most reliable results for determination of the hydrogeologic constants. Often, however, the only available data for the wells in an area are the final drawdowns associated with specific pumping tests of short durations. These data can be used to calculate the specific capacity distribution within the area to describe the water-yielding characteristics of the formation(s) that the wells tap.

GROUNDWATER AND THE HYDROLOGIC CYCLE

The hydrologic cycle is a concept that considers the processes of motion, loss and recharge of the Earth's water (Gray, 1970). Water that evaporates from the land and oceans is carried by the air masses and eventually precipitate either on land or oceans. Some of the precipitation that falls on land may be intercepted or transpired by plants and returns back to the atmosphere, some may runoff over the land surface to streams, and the remainder may infiltrate into the ground.

The infiltrated water may be temporarily retained as soil moisture or move laterally as interflow within the soil to the nearest stream. The remainder percolates deeper to the water table to be stored as groundwater. The groundwater, in turn, may be used by plants, or flow out as springs, or seep into streams as baseflow, only to be eventually evaporated to the atmosphere to complete the hydrologic cycle.

From the foregoing it is clear that the hydrologic cycle is made up of several interrelated components (processes). Therefore, in order to study one of these components in detail, it is necessary to consider its relationships with all the other components.

SOIL MOISTURE AND GROUNDWATER RECHARGE

Excluding precipitation, which is the primary source of groundwater recharge, the status of the soil moisture component is the decisive factor when it comes to groundwater recharge. The zone of soil moisture is at critical juncture in the hydrologic cycle. From the initial impact of precipitation on the soil surface to the final drainage or evaporation of water from the soil, it presents many facets. Thus, the infiltration process, the storage of water within the soil profile, the transmission of water laterally as interflow or vertically as groundwater recharge, the evaporation of the stored soil moisture or its utilization by plants, and the freezing-thawing cycles, all are facets of the role the soil moisture plays.

Precipitation is the primary source of water for the replenishment of soil moisture. Lateral transfer of water over the ground surface from topographic highs to lows, and the upward flow of water from the groundwater zone to the unsaturated zone provide further sources of replenishment to soil moisture.

The primary mechanisms for soil moisture depletion are through evapotranspiration and gravity drainage. The magnitude of evapotranspiration is controlled by the soil moisture availability and the climatic conditions. Gravity drainage, on the other hand, occurs in response to pressure gradients either vertically or laterally. Whereas the lateral movement of the soil moisture generates interflow, the downward vertical movement contributes to groundwater recharge (Singer, 1981).

TIMING OF GROUNDWATER RECHARGE IN THE CREDIT RIVER WATERSHED

The process of groundwater recharge within a watershed is completely controlled by the status of soil moisture, provided that there is no gain to the groundwater storage from outside the watershed. There is a confusion in the minds of many people regarding groundwater recharge. The impression some people have is that groundwater recharge is limited to certain areas in the watershed. This is not true. Except in river and stream valleys that constitute the main groundwater discharge zones, groundwater recharge occurs everywhere else in the watershed. The rate of groundwater recharge, however, is very high in certain areas and the identification of such areas is very important for the appropriate management of the groundwater resources in a watershed.

Measurements of static water level variations at observation wells located at various parts of a watershed are the best means to determine the periods of groundwater recharge. When discussing groundwater recharge, it is important to keep in mind that the groundwater storage is continually being depleted by discharge to streams. Therefore, when the static water level in an observation

well remains steady the groundwater recharge and discharge are equal. A rise in the static level indicates that recharge is more than discharge, a fall means the reverse is true. Unfortunately, such a network of observation wells is not available in the Credit River watershed. Therefore, data from the Blue Springs Creek watershed (Coward and Barouch, 1978), which is located to the west of the study area will be used along with local climatological data to describe the timing of groundwater recharge.

Recharge to groundwater occurs at a maximum rate when the soil is in a state of complete saturation and diminishes when the soil is at the wet limit (field capacity). Within the Credit River watershed, this condition is met mainly during the snowmelt and spring rainfall events, which usually extends from the last week of March through April and early May (Figure 9).

During this period temperatures start to rise, signalling the arrival of spring. The soil moisture is close to saturation and evapotranspiration is low. The snow pack is sharply depleting until it vanishes completely. A vast amount of liquid water, produced by melting snow and rainfall events, is suddenly available in the watershed. Part of this water generates high flows and floods. The remaining water infiltrates through the soil and then percolates to the groundwater storage. This is the period of major groundwater recharge in the watershed when the water table reaches a maximum height and the groundwater storage is at its peak.

Rainfall events that occur during the period from late October to early December also contribute to groundwater recharge. During this period, the temperature is declining, the growing season is finished, evapotranspiration is low, and soil moisture is being restored to saturation level by precipitation that is mostly in the form of rain. The net result is recharge to groundwater and rising water tables. Finally, some recharge to groundwater could take place during winter warm spells.

During the summer and early fall, the soil moisture is utilized mainly by the plants through evapotranspiration and a state of soil moisture deficiency usually prevails. Therefore, most of the infiltrated water from the rain, during this period, is used to satisfy this deficiency with little or no water left to recharge the groundwater. As a result, groundwater levels steadily decline except during heavy rainfall events.

GROUNDWATER OCCURRENCE IN THE BEDROCK

Within the study area, groundwater occurs in the bedrock primarily in openings such as joints, bedding planes, fractures or solution cavities. The availability of water stored in these openings is dependent on the degree of interconnection of the openings.

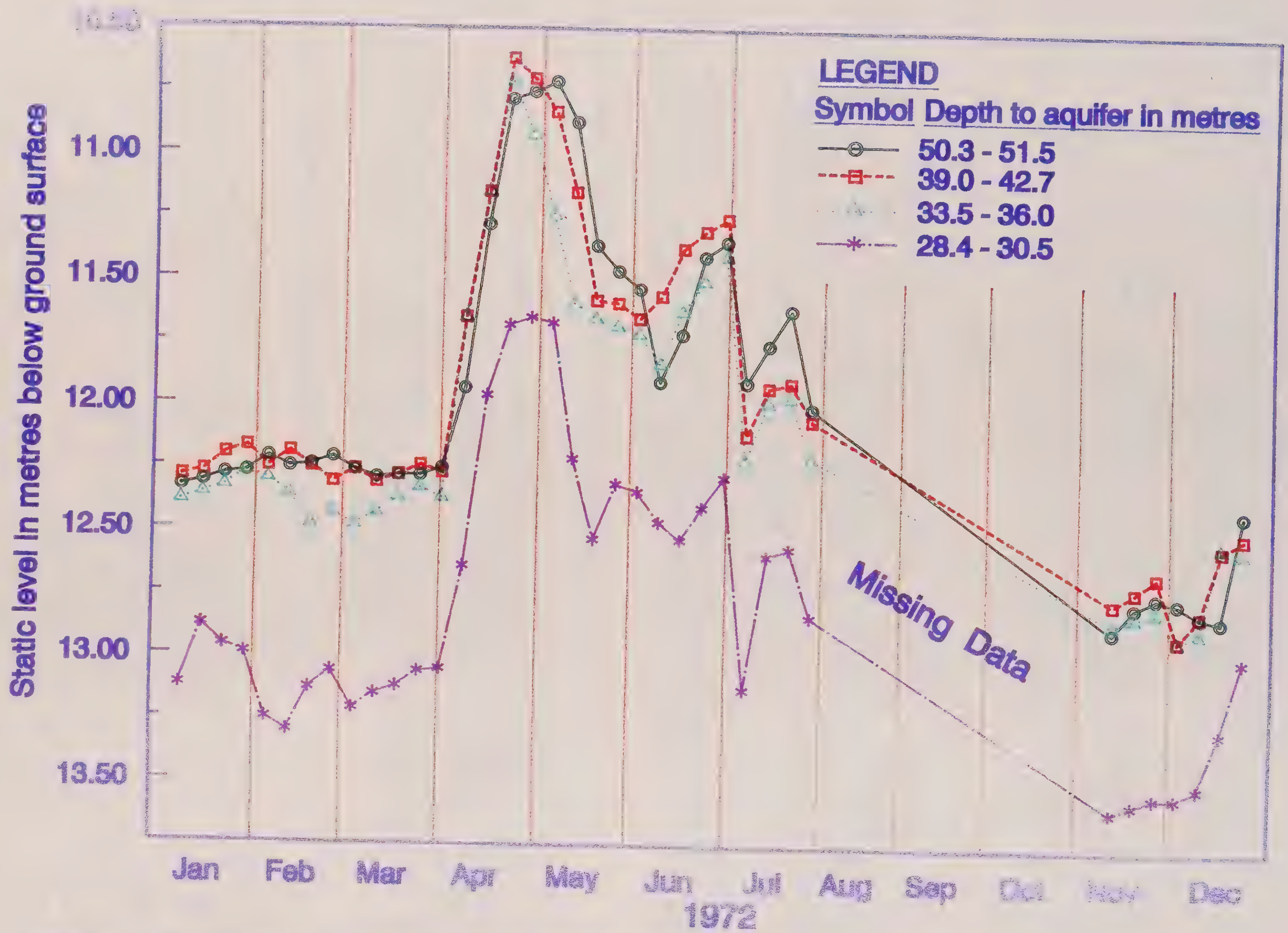


Figure 9. Static Water Level in Well 1B During 1972 in the Blue Springs Creek Watershed (after Cowan and Barouch, 1978).

Solution cavities usually develop in limestone rocks, but they can occur in dolomite and other water soluble rocks. Land forms that have been developed predominantly by solution cavities are known as karst. Coward and Barouch (1978) describe some small karstic caves within the dolomite of the Amabel Formation near Rockwood some 9 km to the west of Acton outside the watershed. They also describe the existence of some small sinkholes in the Blue Springs watershed occurring in areas where the dolomite bedrock is exposed or covered by a thin layer of till. Based on this evidence, it is possible to conclude that some openings within the dolomite rocks of the Amabel and Guelph Formations in the study area may be solution cavities.

BEDROCK HYDROGEOLOGIC UNITS

A number of technical reports, compiled during investigations to provide a number of communities with water supplies, have identified aquifers and gave them local names. In this document, an attempt will be made to describe the water-yielding capabilities of various hydrogeologic units and identify their roles as being aquicludes or good, medium or poor aquifers

The principal hydrogeologic units within the bedrock in the Credit River watershed are: the Georgian Bay Formation, the Queenston Formation, the Cataract Group, the Clinton Group, the Amabel Formation, and the Guelph Formation.

Georgian Bay Formation Hydrogeologic Unit

The Georgian Bay Formation is the oldest Palaeozoic rock in the study area, and it underlies the lower part of the watershed. The Formation consists of shales interbedded with limestone. Groundwater occurs in the Formation in the upper 3-5 m. There are a few wells in the Formation and it constitutes a poor water bearing hydrogeologic unit with specific capacities ranging from 0.5 to 10 L/min/m. From a hydrogeologic point of view, this hydrogeologic unit constitutes an aquiclude.

Queenston Formation Hydrogeologic Unit

The Queenston Formation consisting of red shale underlies most of the area of the watershed below the Escarpment and has been encountered in several wells in the Orangeville area at depths ranging from 70 to 80 m. The pore space in the compact, dense shale has relatively poor interconnection and does not readily fracture or dissolve, thus limiting the effective porosity of the Formation. Only the top 3-5 m of the Formation are weathered and may provide sufficient water supplies to meet domestic requirements. Dames and Moore, Canada (1992), indicates that on the west side of the Credit River from Terra Cotta to Inglewood, a number of domestic wells obtain water from the Queenston Formation. These wells generally produce about 10 L/min using the maximum

available drawdown, often to the bottom of the well. The specific capacity values for wells completed in the Queenston Formation range from less than 0.5 to 20 L/min/m. For all practical purposes, the Queenston Formation is an aquiclude.

Cataract Group Hydrogeologic Unit

The Cataract Group occurs in the Cataract-Credit Forks area, and along the West Credit River north of Belfountain, and in the Orangeville area. It consists, from bottom to top, of a sequence of sandstone (about 5 m), dolomite (about 5 m), and shale (10 m). Specific capacity values of wells completed in Manitoulin Formation of the Cataract Group range from 1.5 to 20 L/min/m. Due to the composition of the Cataract Group and its peculiar areal extent under the Amabel Formation, it does not constitute an important aquifer in the Credit River watershed.

Clinton Group Hydrogeologic Unit

The Clinton Group is limited in terms of areal extent to the west of the Escarpment. From a hydrogeologic point of view, the Clinton Group, being a thin layer of dolomite, can be combined with the dolomite of the Amable Formation and treated as a single hydrogeologic unit.

Amabel Formation Hydrogeologic Unit

The Amabel Formation is one of the most important and productive bedrock aquifers in the Credit River watershed. Many fissures, joints, bedding planes and solution cavities within the dolomite of this Formation have developed an interconnected network that is favourable for the storage and transmission of water. As in any bedrock formation, the amount of interconnected openings varies greatly from place to place and determine the Formation's capability to store and transmit water at any given location.

The aquifer is generally adequate to meet domestic requirements and at certain favourable locations can provide adequate municipal supplies. Specific capacities of wells that tap the Formation range from 1 to 1000 L/min/m.

Guelph Formation Hydrogeologic Unit

The Guelph Formation occurs in a small area at the extreme northwestern part of the watershed. The Formation consists of dolomite that rest on top of the Amabel Formation. Thus, both Formations, from a hydrogeologic point of view, act as one aquifer. Within the study area, wells that tap the Guelph Formation have specific capacities that range from 2 to 300 L/min/m.

HYDRAULIC PROPERTIES OF BEDROCK HYDROGEOLOGIC UNITS

The hydraulic properties of a hydrogeologic unit are expressed quantitatively by the coefficients of transmissivity, hydraulic conductivity, and storage. These properties can be estimated using pumping test data.

There are a number of methods to calculate the aquifer constants from pumping test data. The most widely used methods are based on:

- measurement of drawdown in an observation well during pumping,
- measurement of drawdown of the pumped well during recovery, and
- drawdown-distance method, using the drawdowns in the observation and pumped wells at the end of the pumping period.

Unfortunately, only a few data on pumping tests are available for wells in the watershed and most of the data is incomplete. On the other hand, thousands of specific capacity values, based on short-duration pumping tests, are available for wells within and around the watershed. These data will be used to supplement the data on pumping tests.

Hydraulic Properties Based on Pumping Tests

Data on 29 wells, drilled as part of providing municipal water supplies to various communities, are available. Of these wells, 16 wells were drilled in the Amabel Formation, 8 wells likely tap the Amabel Formation, and one well likely taps the Queenston Formation. The water bearing formations that the remaining 4 wells tap could not be determined.

The locations of these wells are shown on Figure 10 and a summary of their characteristics in terms of location, elevation, lithology, depth at which water was found, static level, pump level, pumping rate, testing time, hydraulic coefficients, well construction details, type of aquifer, and date of well completion is given in Appendix I.

The transmissivities (m^2/day) and the storage coefficients (dimensionless) of the Amabel Formation were determined for a number of wells as part of the hydrogeologic investigations that was carried out in conjunction with finding water supplies to some communities in the watershed.

The following is a summary of the available data for these wells:

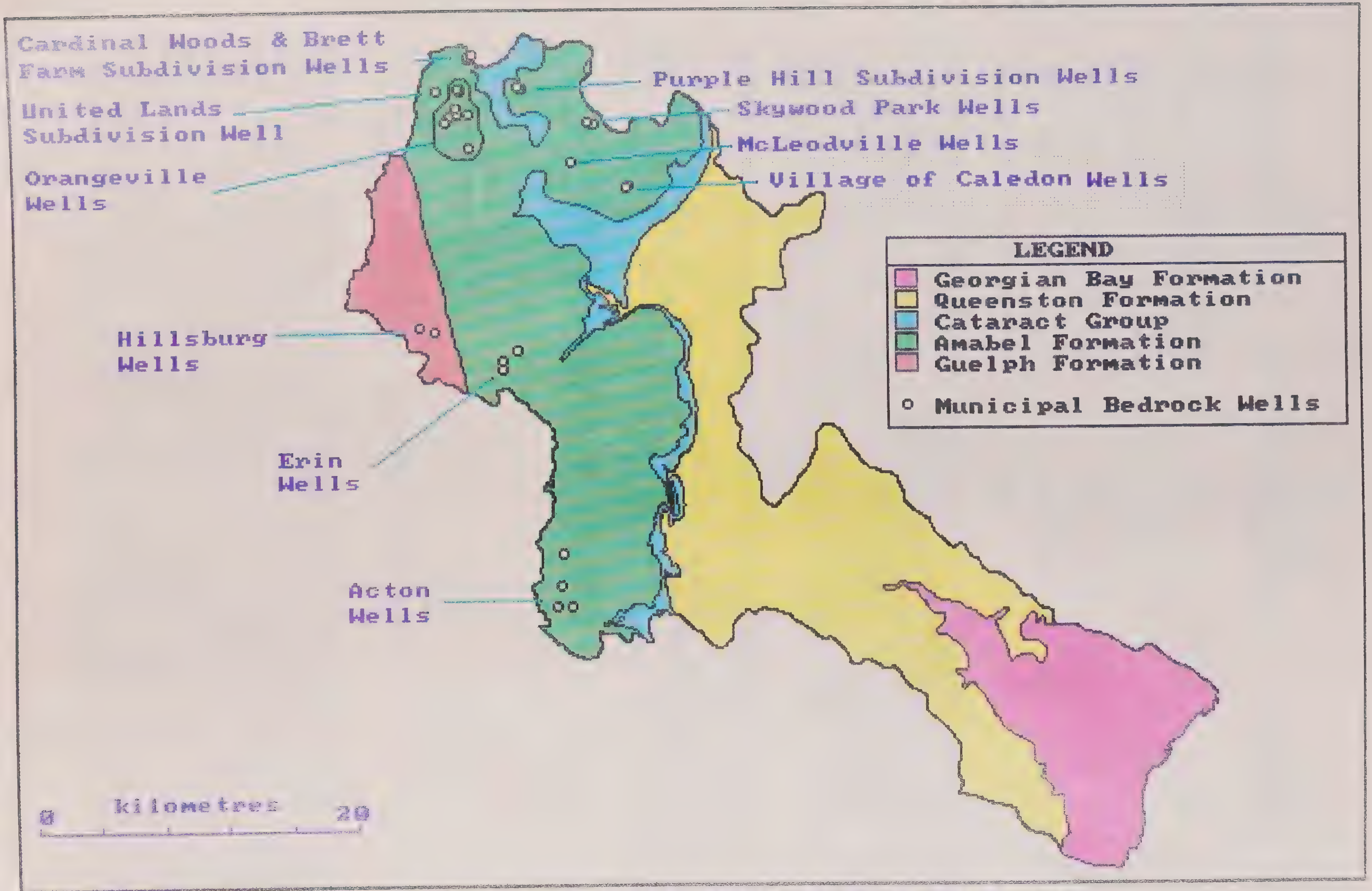


Figure 10. Locations of Municipal Wells Drilled in the Bedrock

Well No. and Location	**Transmissivity m^2/day**	**Storage Coefficient**
Brett Farm Subdivision in Mono Township	150	0.0003
Erin well No. 7	40-70	------
Erin well No. 8	380	0.0001
Acton well No.869	1153-1460	0.001-0.1
Orangeville well No. 9	181	------

The storage coefficients for the Amabel Formation, presented above, range from 0.1, which is generally indicative of a high aquifer transmissivity to $1*10^{-4}$, which is indicative of low porosity and/or a thin aquifer. As the Amabel Formation is fairly thick, it can be concluded that its porosity and water-yielding capability are highly variable, rendering the effective thickness of the aquifer considerably smaller than the measured thickness. This is to be expected in fractured bedrock.

Evaluation Transmissivities from Specific Capacity Data

Theis et al (1963) describe a method for estimating the transmissivity of an aquifer from the specific capacity of a well. Their analysis is based on the Jacob equation, given in consistent units as:

$$T = (Q/12.6\ s)\ \ln\ [(2.25\ T * t)/(r^2 * S)] \qquad (1)$$

where

T = transmissivity (L^2/t),
Q = discharge (L^3/t),
s = drawdown in the well (L),
t = pumping time (t),
S = storage coefficient (dimensionless), and
r = radius of the well (L).

Because T appears twice, equation (1) cannot be solved directly. Graphical solutions involving matching the specific capacity data to a family of curves were proposed. These solutions, however, have the disadvantage of requiring a different set of curves for every possible combination of well radius, pumping period, and storage coefficient. In addition, any corrections for partial penetration or well loss require additional calculations. A computer program that uses an iterative technique, corrects for partial penetration and well loss, and provides a rapid estimate of transmissivity at hundreds of data points, was developed by Bradbury and Rothschild in 1985. This program was modified to

accept the format of the MOEE WWIS data, and was linked to the MOE Groundwater RAISON System to allow for the use of contour mapping routines and statistical programs.

Using the above computer program, the transmissivity values for wells completed in bedrock were determined. To determine the statistical distribution, mean and range of the transmissivity values, a statistical analysis was applied to wells completed in the various hydrogeologic units. The transmissivity values in each unit were listed in ascending order of magnitude and assigned probabilities according to the relationship:

$$F = (100 * m) / (n + 1) \qquad (2)$$

where

F = percentage of wells where transmissivities are less than the transmissivity of well of serial number m,
m = serial number of well arranged in ascending order of transmissivity, and
n = total number of wells.

The transmissivity values for various units were then plotted against the percentage of wells on logarithmic probability paper. The transmissivity values plot as approximately straight lines indicating that the samples have lognormal frequency distributions. Therefore, it could be concluded that the most probable transmissivity value for a given hydrogeologic unit is equal to the geometric mean of its individual transmissivity values.

The logarithmic probability plots for various bedrock hydrogeologic units in the Credit River watershed are shown in Figures 11 and 12 and the number of wells, 10 percentile, mean, and 90 percentile transmissivity values are given in Table 7.

The 10 and 90 percentile values are the transmissivities not exceeded by 10% and 90% of the wells, respectively. They provide a measure of the dispersion of the transmissivity values; a large difference between the 10 and 90 percentiles indicates a large spread and a high standard deviation.

GROUNDWATER OCCURRENCE IN OVERBURDEN

The overburden in the study area is composed of glacial, glacio-fluvial, glacio-lacustrine, and recent deposits. Overburden materials vary in composition and grain size from clay to bolders. Groundwater occurs within the overburden in the pore spaces between the grains of the unconsolidated materials.

Clays, though highly porous, have such small pore spaces that a large percentage of the water contained in them is bound to the

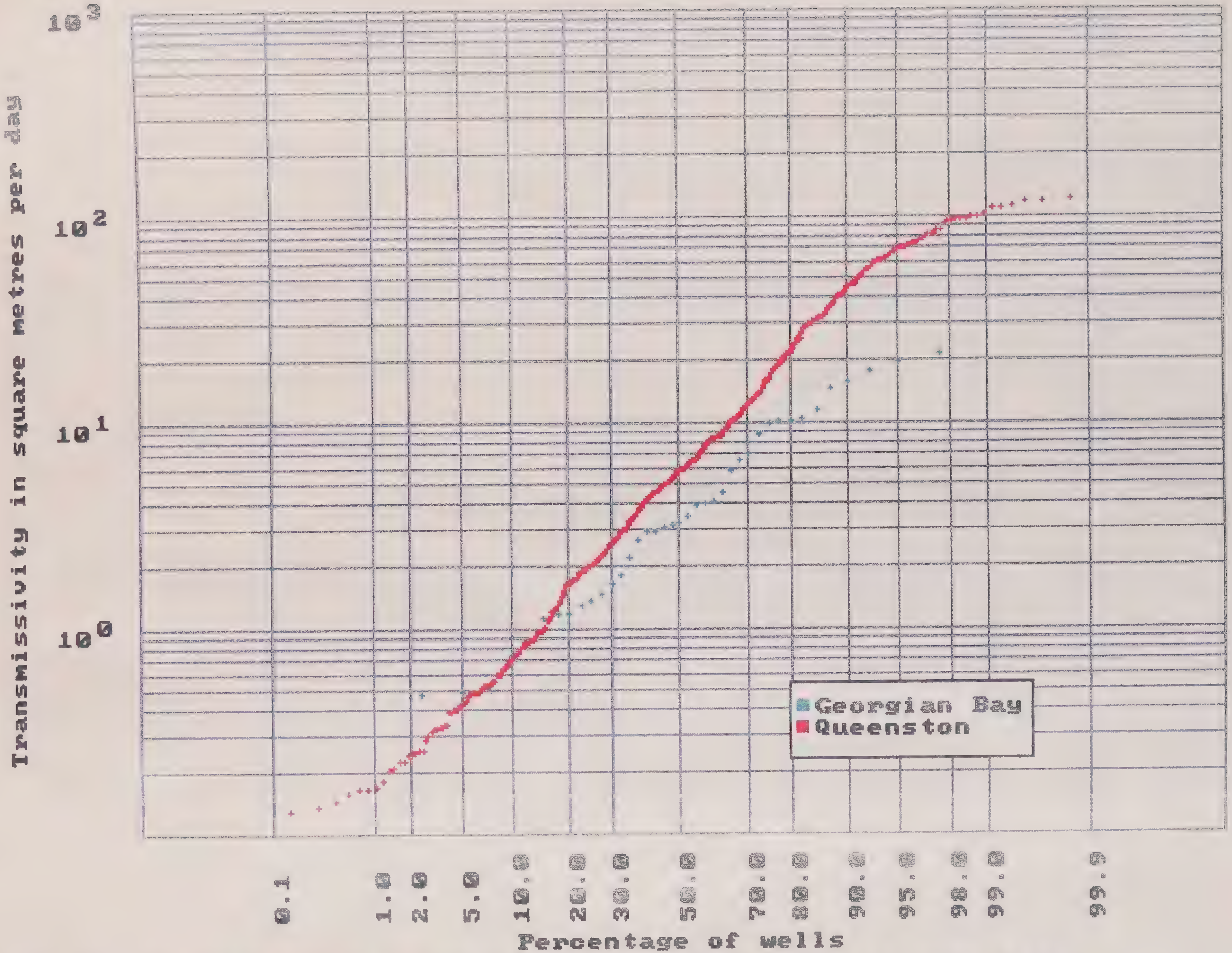


Figure 11. Transmissivity - probability graph for wells completed in the Georgian Bay and Queenston hydrogeologic units

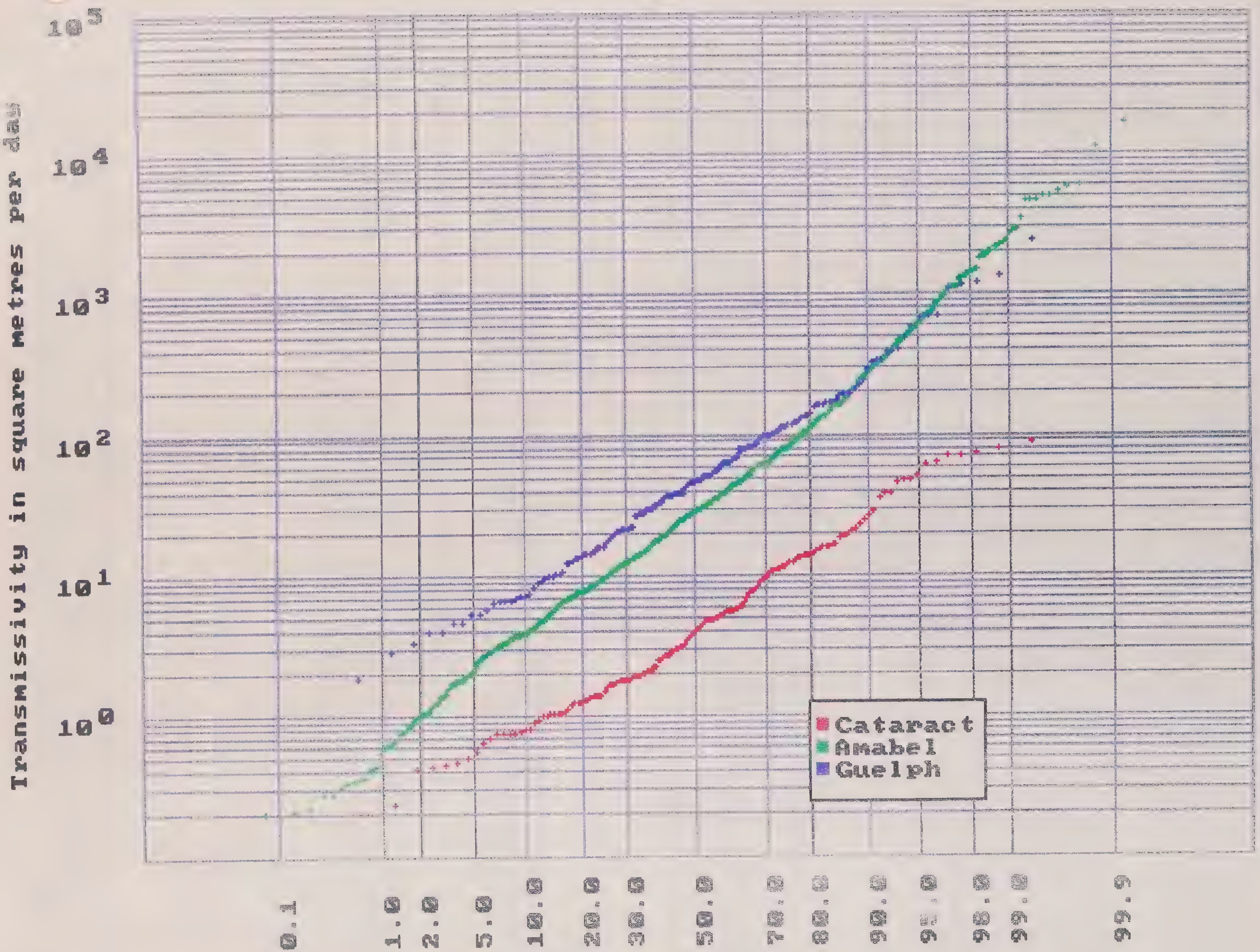


Figure 12. Transmissivity - probability graph for wells completed in the Cataract, Amabel, and Guelph hydrogeologic units

particles by forces of molecular adhesion. Clay-rich sediments are usually described as being impermeable. The coarse grained sand and gravel deposits, on the other hand, have large pore spaces that allow water to move more freely. These deposits constitute the best aquifers within the overburden in the study area.

As is the case with the bedrock, the openings within the overburden and the degree of their interconnections are highly variable. Further, the areal distribution of various water-bearing materials, their thicknesses, geologic settings, and opportunity for being recharged are also highly variable. Sand and gravel materials in particular have been deposited in a rapidly changing environment, which also produced layers of fine sand, silt and clay within the coarser materials. All these factors have important implications when it comes to the availability and magnitudes of water supplies locally, and for movement of groundwater on a watershed basis (see Section on Groundwater Movement).

In general, the availability of ground water in the overburden ranges from poor to good. Most wells in the overburden are used for domestic supplies and livestock requirements. Locally, overburden aquifers are the most productive sources of groundwater within the study area and provide a number of municipalities with water supplies. Given the heterogeneity of these aquifers, detailed local investigations including test wells are necessary to find appropriate water supplies.

OVERBURDEN HYDROGEOLOGIC UNITS

The following hydrogeologic units occur in the study area: sandy silt to sand till, silt to clayey silt till, ice-contact stratified drift, meltwater channels, and glacio-lacustrine deposits.

Sandy Silt to Sand Till Hydrogeologic Unit

Three tills are included in this hydrogeologic unit: Wentworth Till, Newmarket Till, and Port Stanley Till. Till analyses conducted on these tills in the Orangeville area (Cowan, 1976) indicate the following mean percentage values:

Till	Clay %	Silt %	Sand %
Wentworth Till	11	39	50
Newmarket Till	10	36	54
Port Stanley Till	12	39	49

The above data indicate that the three tills contain a high percentage of sand and silt. Because of this similarity in composition, the tills can be viewed, from a hydrogeologic point of view, as one hydrogeologic unit that constitute an important

aquifer in the study area.

Data are available on short-term pumping tests for 102 wells completed in the sandy silt to sand till hydrogeologic unit. No data, however, are available on long-term pumping tests. The specific capacity data for the 102 wells range from 0.3 to 200 L/min/m.

Silt to Clayey Silt Till Hydrogeologic Unit

This unit consists of two tills: the Tavistock Till and the Halton Till. Analyses on 49 samples of the Tavistock Till (Cowan, 1976) give average values of 28% clay, 53% silt, and 18% sand. Analyses of 14 samples of the Halton Till (Funk, 1979) give average values of 36.9% clay, 45.6% silt, and 17.5% sand. The Tavistock Till occupies a very small area in the extreme western part of the watershed. Therefore, this hydrogeologic unit consists mainly of the Halton Till.

Due to its high silt and clay content, the unit is able to provide limited water supplies to meet domestic needs. The unit, from a hydrogeologic point of view, is a poor aquifer. The specific capacity data for 216 wells completed in the unit range from 0.3 to 60 L/min/m.

Ice-contact Stratified Drift Hydrogeologic Unit

The areal distribution of this unit is shown on Figure 13. Wells completed in this unit indicate the presence of gravel, coarse to fine sand, silt, and clay deposits. This highly variable composition result in a highly variable water-yielding capability. Nevertheless, the unit constitutes a major aquifer in the study area and can serve as a major source of water for domestic and municipal needs. The specific capacity data for 193 wells completed in this unit range from 0.6 to 2162 L/min/m.

Meltwater Channels Hydrogeologic Unit

The areal distribution of this unit is shown on Figure 13. Wells completed in this unit indicate the presence of gravel, coarse, medium and fine sand, and some silt and clay. As is the case with the previous unit, the meltwater channels hydrogeologic unit is highly variable in composition and water-yielding capability. Nevertheless, the unit constitutes one of the best aquifers in the study area and can serve as an important source for domestic and municipal water supplies. The specific capacity data for 134 wells completed in this unit range from 0.1 to 2993 L/min/m.

Glacio-lacustrine Deposits Hydrogeologic Unit

This unit outcrops in the lower part of the study area. The sand and silt deltaic deposits of Lake Peel origin constitute the most

important portion of this unit. Due to its composition and limited areal extent, the unit constitutes a minor aquifer in the study area. The specific capacity data for 73 wells completed in this unit range from 0.6 to 100 L/min/m.

HYDRAULIC PROPERTIES OF OVERBURDEN HYDROGEOLOGIC UNITS

A limited amount of data is available on the hydraulic properties of some overburden hydrogeologic units from long-term pumping tests performed on municipal wells. On the other hand, a substantial amount of data is available on short-term pumping tests. Both types of data are described below.

Hydraulic Properties based on Pumping Tests

Data on 14 municipal wells, completed in the overburden, are available. Of these wells, 5 wells are completed in meltwater channels, and 8 wells are completed in ice-contact stratified drift. Data for the remaining well are inconclusive. A summary of the characteristics of these wells is given in Appendix II.

One pumping test conducted on Test Well No. 5, which is drilled in a meltwater channel in the Village of Inglewood, indicates a transmissivity value of approximately 45 m^2/day. Another test conducted on Alton Municipal Well No.3, which is drilled in a different meltwater channel, indicates a transmissivity of 2382 m^2/day and a storage coefficient of 0.001. One pumping test was conducted on Coles Industrial Development Well No.1, located in Mono Township, indicates a transmissivity value of 65 m^2/day. The well is completed in ice-contact stratified drift.

Evaluation of Transmissivity from Specific Capacity Data

The specific capacity data for wells completed in various overburden hydrogeologic units were used to compute the transmissivity values for these units. The transmissivity values were then analyzed using Equation 2 and transmissivity-probability graphs were produced (Figures 14 and 15). Again the transmissivity values for various units plot approximately as straight lines, indicating lognormal distributions. The number of wells in each unit, the 10 percentiles, means, and 90 percentiles are given in Table 8.

GROUNDWATER MOVEMENT AND DISCHARGE ZONES

Groundwater is subject to continuous movement, the rate of which is a function of the hydrogeologic characteristics of the material in which it moves, the existing hydraulic gradients, and temperature. The existence of a three-dimensional, continuous groundwater domain in a corresponding three-dimensional potential field has been

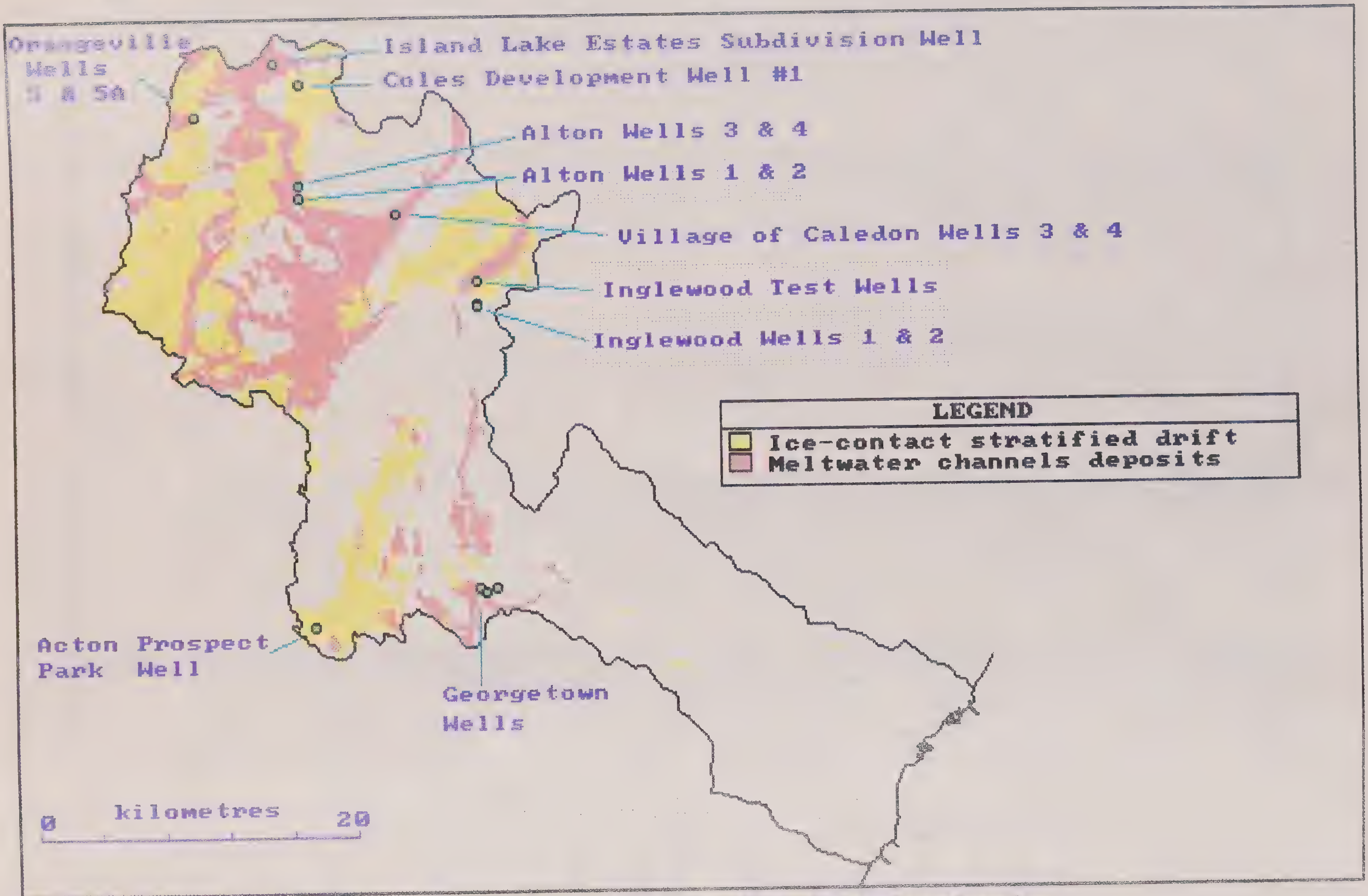


Figure 13. Locations of Municipal Wells Drilled in Overburden

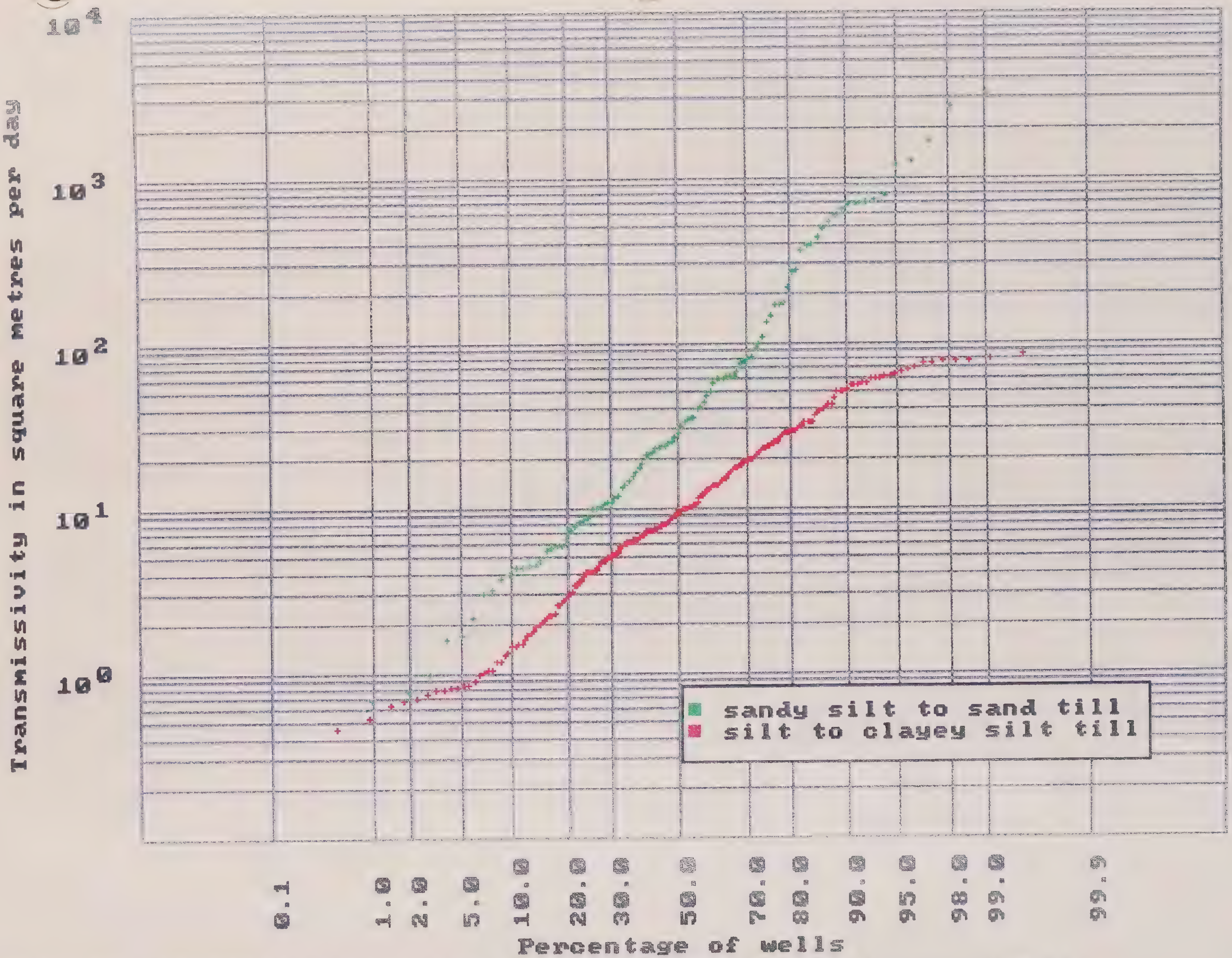


Figure 14. Transmissivity - probability graph for wells completed in sandy silt to sand till and silt to clayey silt till

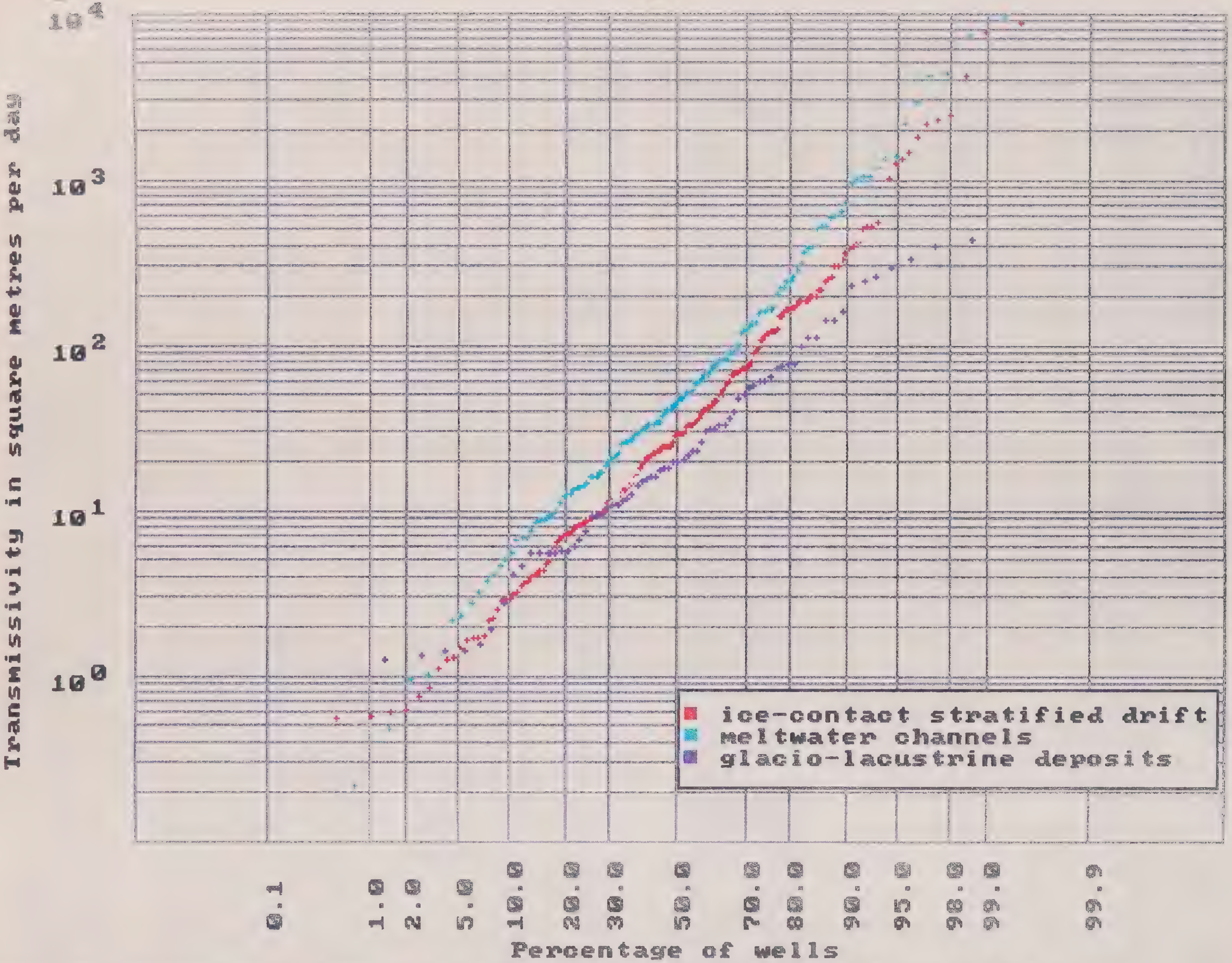


Figure 15. Transmissivity - probability graph for wells completed in ice-contact stratified drift, meltwater channels, and glacio-lacustrine deposits

established and developed by Hubert (1940), To'th (1962, 1963), and Freeze and Whitherspoon (1966, 1967).

The groundwater hydraulic potential at a given point in this domain where the flow is at low velocity (Darcian) is given by:

$$H = g * z + (AP - P)/d \qquad (3)$$

where

H = hydraulic potential at a given point in the field,
g = gravity acceleration,
z = elevation at the point above an assumed datum,
AP= atmospheric pressure,
P = pressure at a given point, and
d = density of water.

The hydraulic head equals the hydraulic potential divided by the gravity acceleration and is measured in metres above a datum (usually above mean sea level). Because the hydraulic head is obtained by dividing the hydraulic potential by a constant, it is a potential quantity itself and obeys the laws of potential theory. The hydraulic head, therefore, can be used as a potential function to describe the groundwater flow system.

Measurements of hydraulic head is usually done using a piezometer inserted in an observation well. The piezometer provides readings of the hydraulic head at a given point in the well. A number of piezometers can be inserted at different levels inside the well to provide hydraulic head readings at these levels. This is usually done if the well penetrates more than one aquifer. Many observation wells are needed to provide readings of the hydraulic heads at a given time in order to construct an accurate map of the hydraulic head distribution within a given aquifer. This can be a very expensive operation.

As mentioned earlier, no observation wells exist in the study area. However, data on static water levels from thousands of wells completed in the bedrock or the overburden are available. These data were obtained at different times and provide mean readings of the hydraulic heads in various wells. Therefore, they cannot provide an exact picture of the hydraulic head configuration. Nevertheless, given the fact that the differences in hydraulic head readings are small within a well, these data can be used to provide a general picture of hydraulic head (static groundwater level) configuration on a watershed scale.

Knowledge of static water level configuration is of importance in groundwater investigations as it indicates the direction and rate of groundwater flow. Figure 16 and Map 6 show the static groundwater level configuration in the bedrock. It is a subdued

reflection of surface topography where the groundwater divide and local divides coincides closely with the watershed topographic divide and with the local divides. Groundwater flow appears to be towards major river valleys above the Escarpment and towards the Credit River below the Escarpment. The highest elevations are found at the extreme northern and northwestern parts of the watershed above the Escarpment and equal approximately 480 m and the lowest elevation is that of Lake Ontario and equals 75 m.

Figure 17 and Map 7 show the static groundwater level configuration in the overburden and indicate similar patterns to those described for the bedrock.

Based on the above findings, it can be concluded that the valleys of rivers and creeks constitute the major discharge zones in the study area. This conclusion is not surprising. From a watershed perspective, the upper parts of the bedrock contain most of the openings resulting in higher transmissivities in the horizontal directions and decreasing transmissivities in the vertical direction. Similarly, the existence of less permeable, mostly horizontal layers of silt and clay within the overburden, especially within the more permeable sand and gravel deposits, results in transmissivity distributions that are larger horizontally than vertically. The end result is more groundwater flowing horizontally towards the watershed valleys.

QUANTITATIVE ASSESSMENT OF LONG-TERM GROUNDWATER DISCHARGE AND RECHARGE

It is generally recognized that streamflow consists of the following three components:

i direct runoff, which is that part of precipitation that flows over the land surface to the streams;

ii interflow, which is that part of precipitation that flows part of the way underground, but does not become part of the groundwater regime; and

iii baseflow, which is that part of the precipitation that reaches the streams as natural groundwater discharge, after being a part of the groundwater regime.

One way to estimate the groundwater discharge is to separate the streamflow into different components. Unfortunately, the principles of separating the streamflow into components are not well developed, and in the case of complex streamflow events appears to be somewhat arbitrary. It is believed, however, that if a certain method of streamflow separation is followed consistently, the same error will be committed systematically and therefore, useful results can be obtained for comparison purposes.

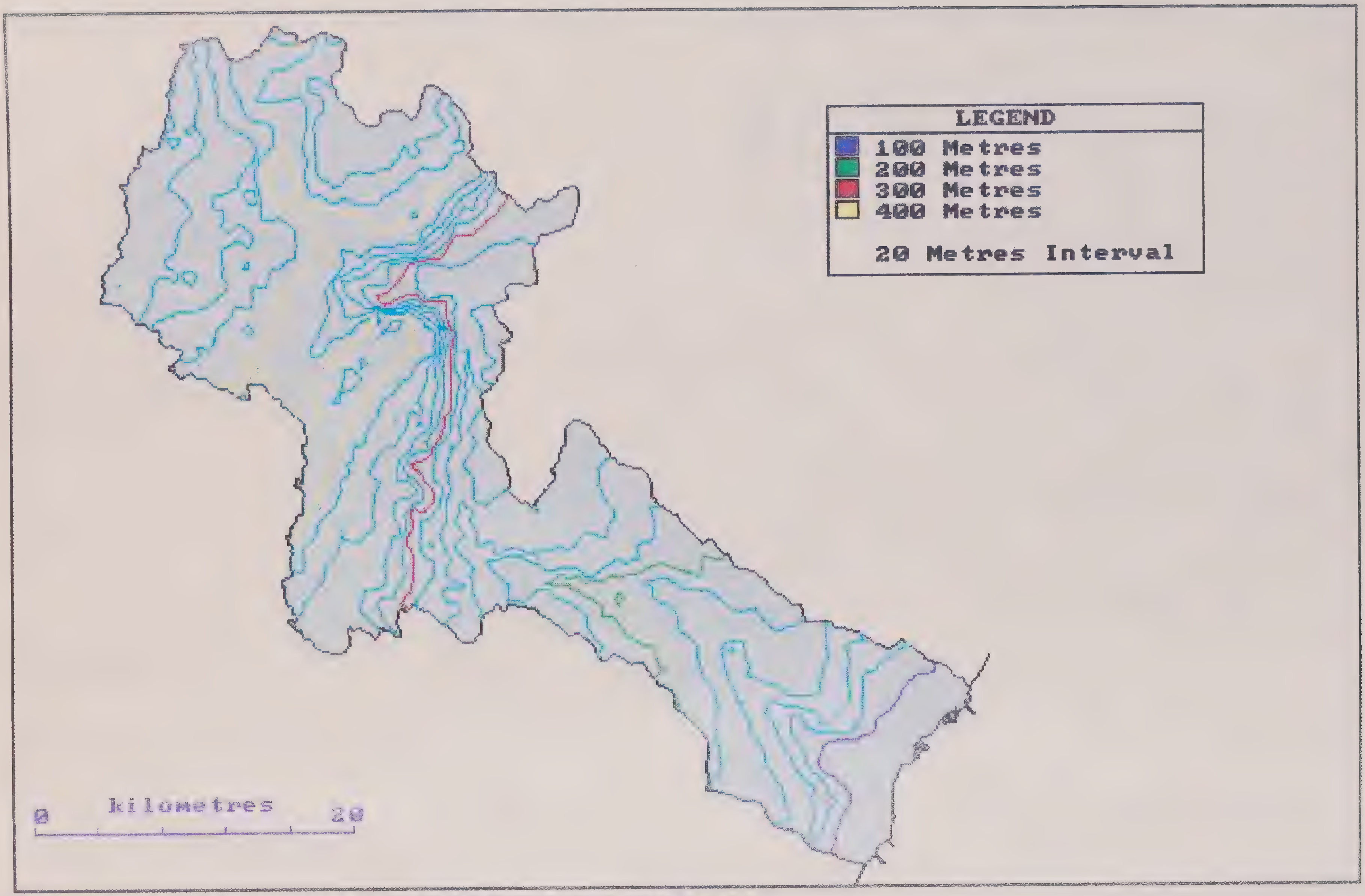


Figure 16. Groundwater Levels in the Bedrock

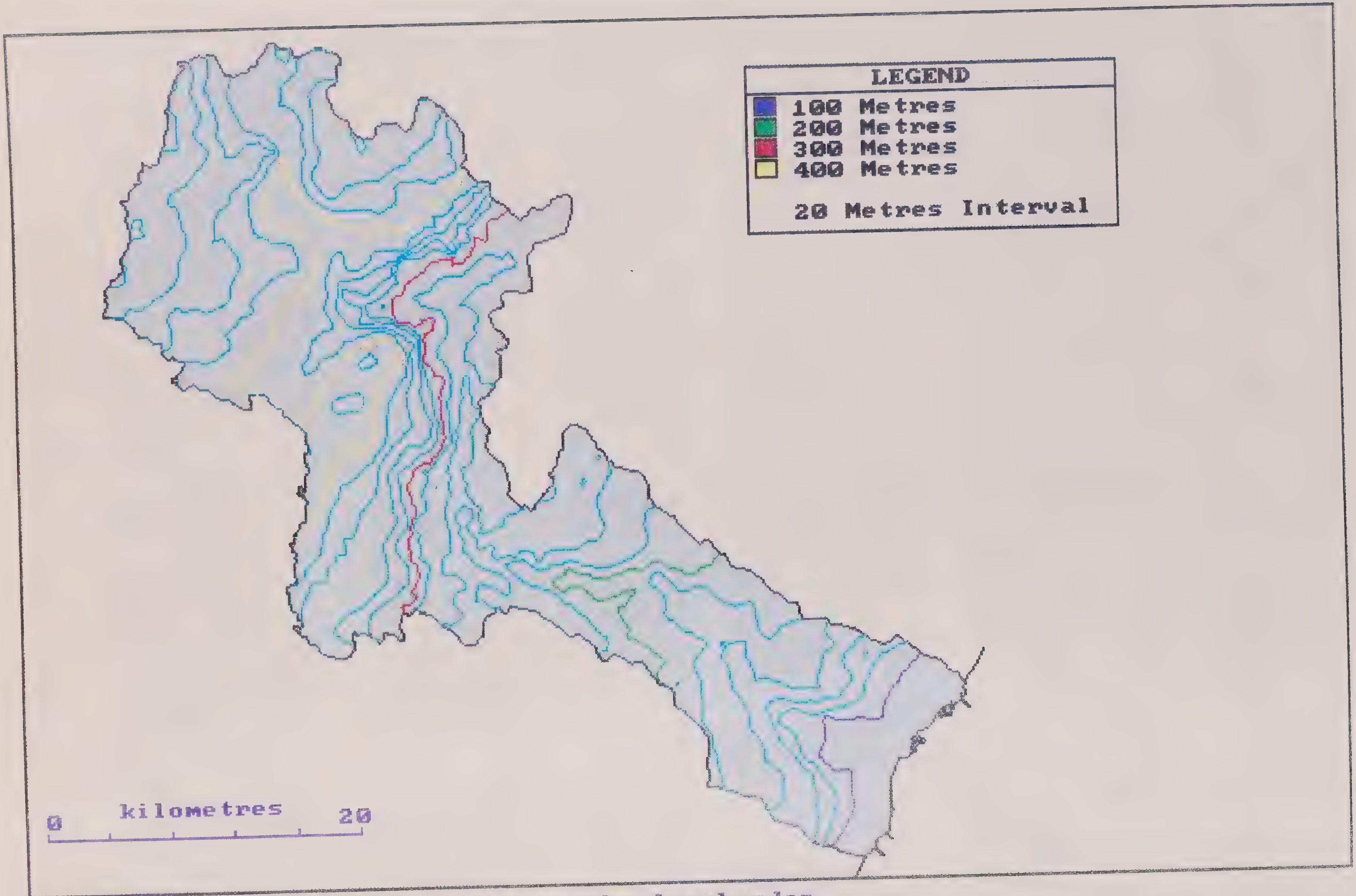


Figure 17. Groundwater Levels in the Overburden

For the purpose of this study, a Streamflow Separation Computer Program was developed. The Program separates streamflow into two components: a surface runoff component consisting of direct runoff and interflow, and a baseflow component.

The Program allows for the processing of a large amount of data in a very short time and ensures consistency in the application of the technique. Six parameters are used in the Program. The first parameter is used to detect the beginning of an event, the second to determine the event period, the third to detect the peak flow, the fourth to determine the value of the groundwater component under the peak, the fifth to determine the relative event limits, and the sixth to determine the absolute event limit. Data from various gauging stations in the watershed were used to separate the streamflows (Figure 18).

Data from seven streamflow gauging stations, located within the watershed, were considered for analysis. Figure 19 shows the locations of these stations, station numbers, and the record periods. The Figure also shows all the sub-watersheds and the segments for which streamflow analyses were performed. The length of the streamflow record differs from one station to the other. The longest records are those for Cataract Station and go back to 1915. The shortest Records are those for Alton Station and extend from 1983 to 1990.

All the available streamflow data were processed using the Streamflow Separation Computer Program. Appendix III gives the computed baseflow values on a monthly and annual basis for the eight gauging stations. The monthly and annual means as well as annual ratios of baseflow to surface runoff baseflow are also included.

An examination of Appendix III reveals that baseflow is highest during the months of March, April and May. Baseflow decreases steadily during the period June-October and starts to recover during November and December. At Orangeville, Alton, Erin, Cataract, and Boston Mills Stations, the baseflow constitutes a large percentage of the total streamflow ranging from 63% to 76%. At Norval S.Cr and Erindale, the baseflow component is much smaller ranging from 48% to 52%.

Concurrent streamflow records that extend from 1987 to 1990 are available for the following stations: Orangeville, Alton, Erin, Norval S. Cr., and Erindale. The 4-year database was used to calculate the long-term annual means of baseflow at these stations and for three segments between stations. The first segment (S3) is the area contained between Orangeville, Cataract, and Alton Stations. The second segment(S5) is the area contained between Cataract, Erin, and Boston Mills Stations. The third segment (S7) is the area contained between Boston Mills, Norval S. Cr., and Erindale Stations.

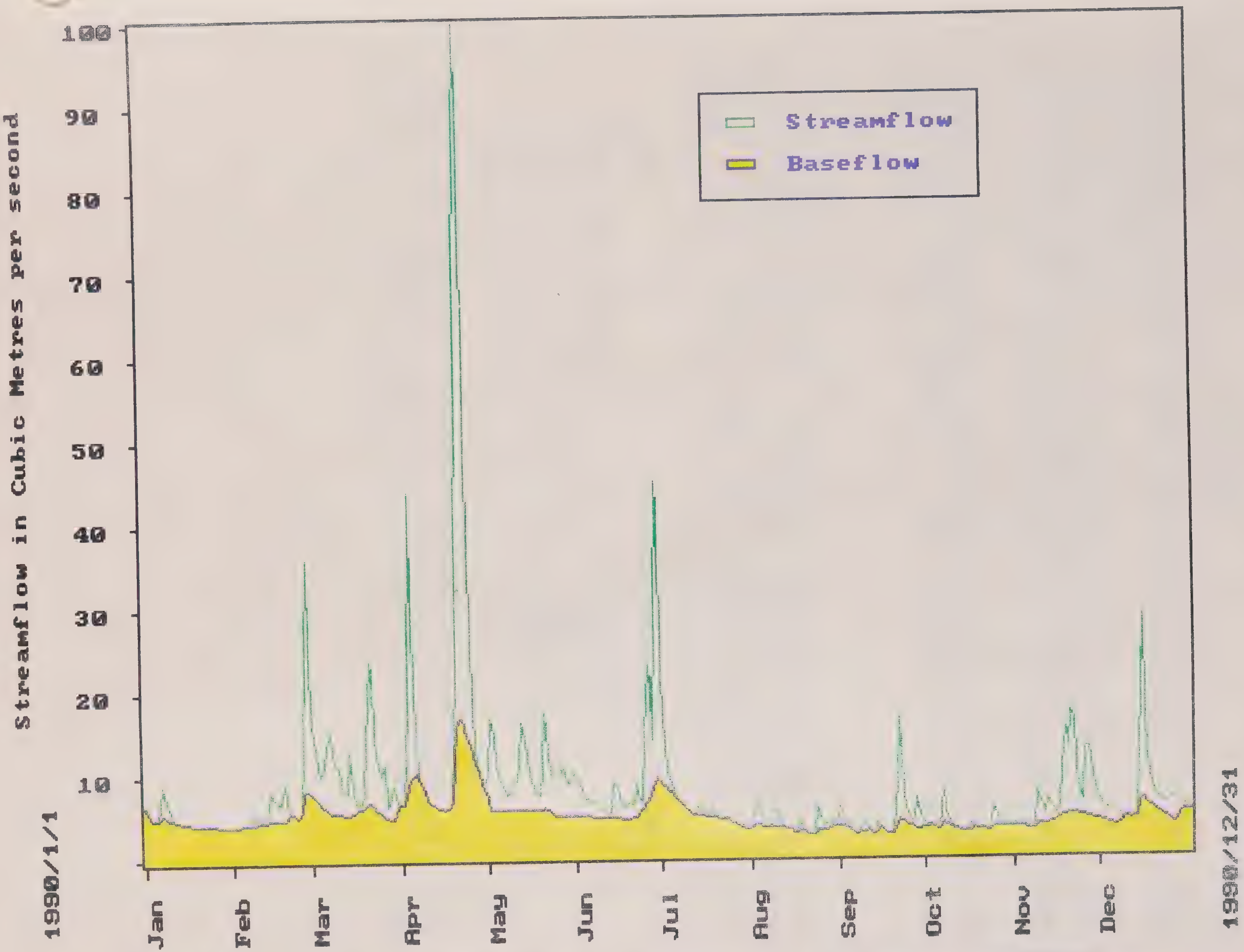


Figure 18. Separation of Streamflow Hydrograph at Station 02HB002 at Erindale for the year 1990

Table 9 provides the results of streamflow analyses for the above stations and segments as well as the drainage areas, and annual surface runoff.

Given that the change in soil moisture storage approaches zero over a long period of time, it is possible to assume that the computed mean annual baseflow values over the period 1987-1990 represent both the long-term mean annual groundwater recharge and discharge.

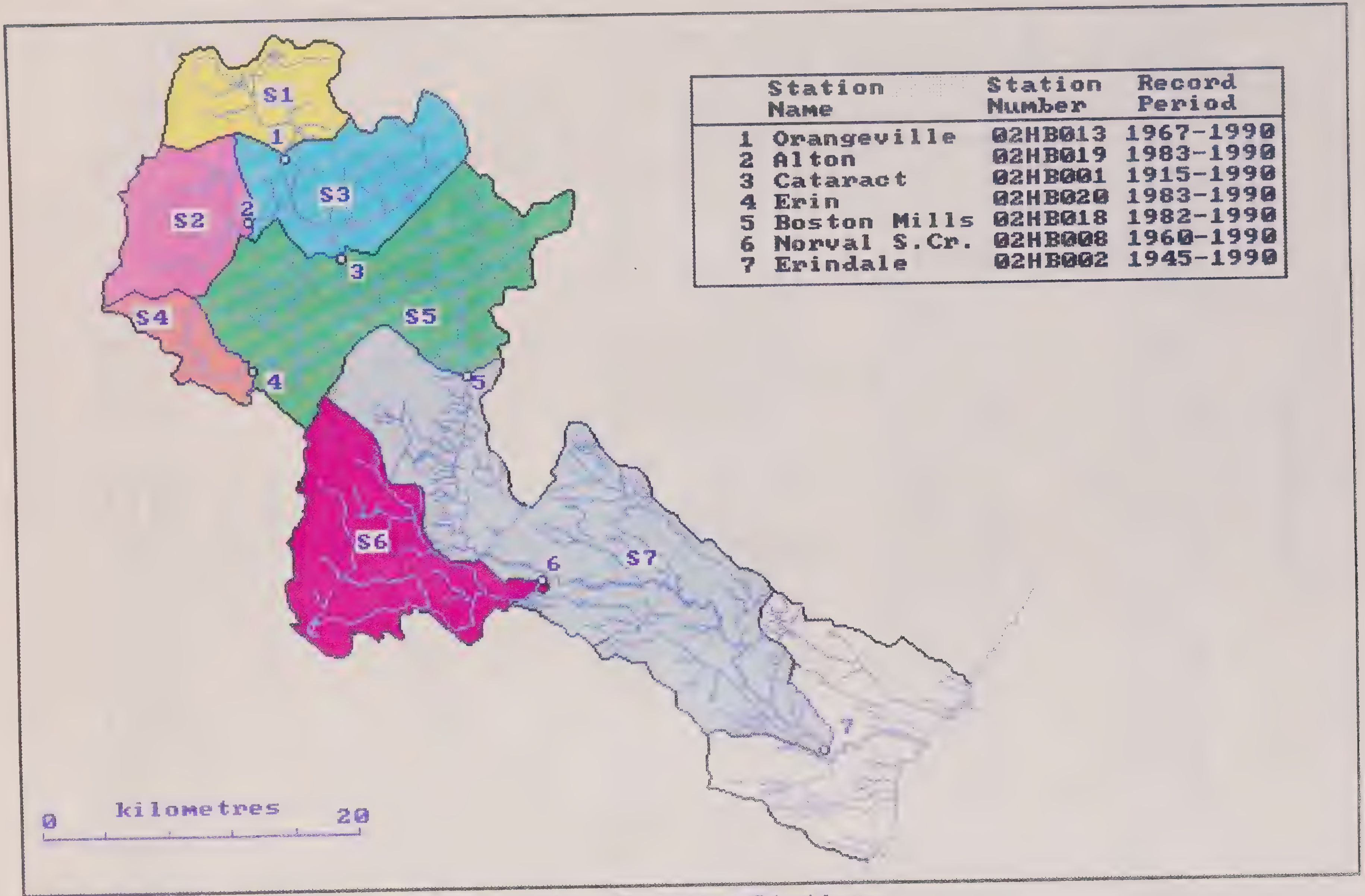
Data from Table 9 were considered along with data on precipitation and surface runoff to calculate a long-term annual water budget for various parts of the watershed. Table 10 gives the details of the water budget calculations.

GROUNDWATER RECHARGE ZONES

The groundwater recharge variations within Credit River watershed can be assessed qualitatively based on geologic considerations as well as on the findings of the investigation of the hydraulic properties of various rocks and of the streamflow analyses. Groundwater recharge capabilities are assigned as follows (Map 8):

UNIT	RECHARGE CAPABILITY
Meltwater channels	very high
Ice-contact stratified drift	high
Sandy silt to sand till	medium to high
Glacio-lacustrine deposits	low to medium
Silt to clayey silt till	low
Bedrock outcrops	low

Most of the high to very high groundwater recharge zones are located above the Niagara Escarpment. A great deal of care is needed to protect these areas from contamination through appropriate land use planning.



	Station Name	Station Number	Record Period
1	Orangeville	02HB013	1967-1990
2	Alton	02HB019	1983-1990
3	Cataract	02HB001	1915-1990
4	Erin	02HB020	1983-1990
5	Boston Mills	02HB018	1982-1990
6	Norval S.Cr.	02HB008	1960-1990
7	Erindale	02HB002	1945-1990

Figure 19. Locations of Streamflow Guaging Stations

HYDROCHEMISTRY

Chemical composition of surface water and groundwater in a watershed is an important consideration in any hydrogeologic study. The suitability of the water for use by industry, commerce, agriculture or for drinking purposes can be assessed by a study of the hydrochemistry.

GROUNDWATER QUALITY

The water well records contain information on the kind of water that was encountered in a well in terms of being fresh, salty, sulphurous, or containing iron or gas. A plot of the kind of water encountered in bedrock and overburden wells in the study area is shown on Map 9. The Map indicates that the majority of wells in the study area have fresh water. A few wells show salty or sulphurous content.

Throughout the years, water quality analyses were carried out on many municipal and private wells. A concerted effort was made during this study to assemble all these chemical data (Appendices IV and V). The data contain information on major conventional parameters such as hardness, alkalinity, and turbidity as well as on heavy metals such as aluminum and copper.

Common chemical parameters of concern in drinking water and their limits as outlined in the Provincial Drinking Water Objectives are:

chloride	250 mg/l
iron	0.3 mg/l
nitrate as nitrogen	10 mg/l
sulphate	250 mg/l
total dissolved solids	500 mg/l

There is no recommended Objective for hardness. A common classification scheme for hardness is as follows:

Hardness Range mg/l of $CaCO_3$	Type of Water
10 - 60	soft
61 - 120	moderately hard
121 - 180	hard
> 180	very hard

An examination of the water quality database for bedrock wells indicate that the majority of these wells have very hard water. The majority of samples show chloride concentrations between 0.1 and 245 mg/l. Seven samples, however, show concentrations above

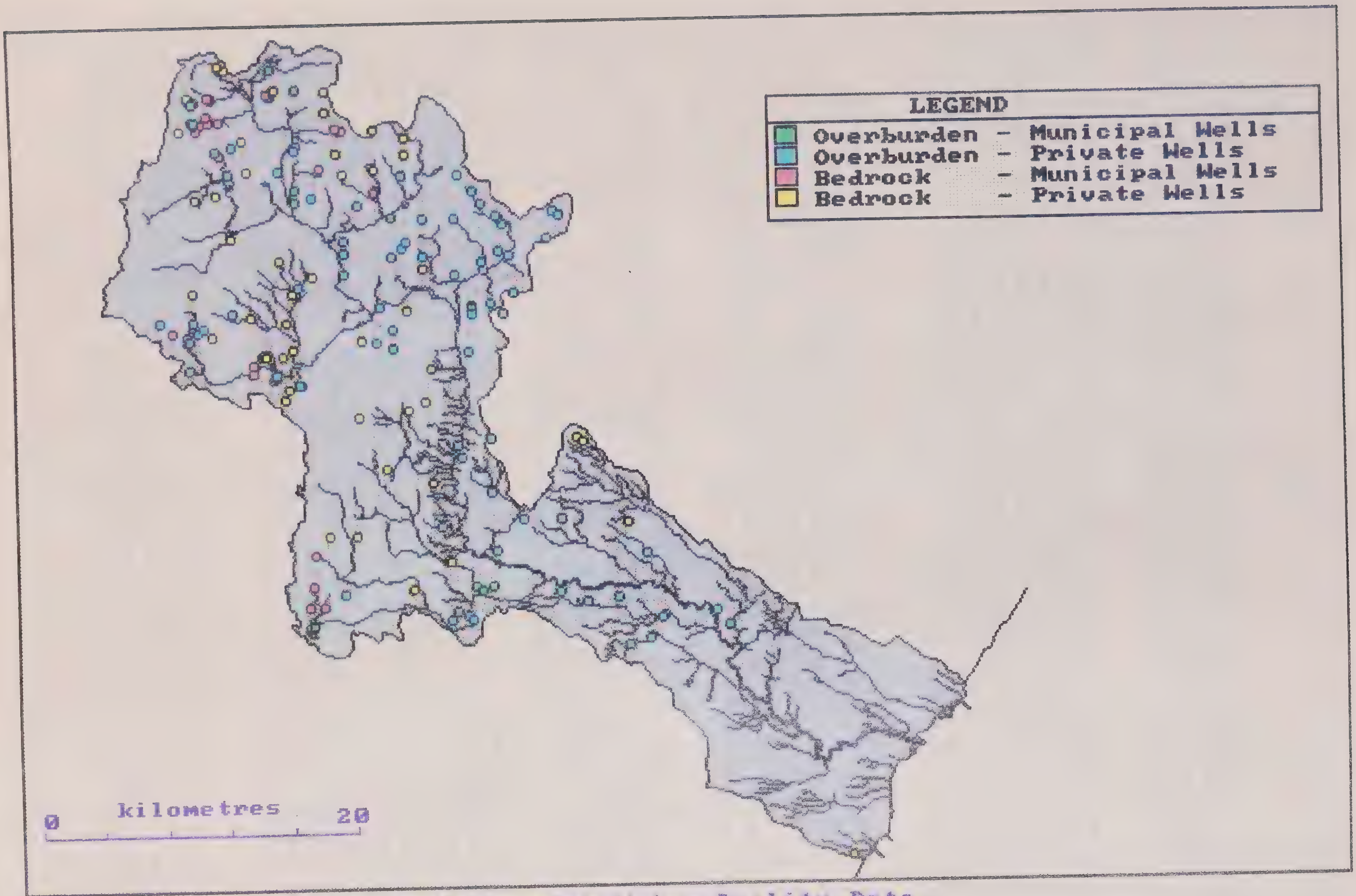


Figure 20. Locations of Wells with Water Quality Data

250 mg/l.

The majority of samples show nitrate concentrations much below 10 mg/l, indicating that the bedrock has not been subjected to any contamination. The majority of samples show iron concentrations above 0.3 mg/l. These elevated iron concentrations are most likely due to high iron levels in the bedrock.

The majority of samples show sulphate concentration between 10 and 184 mg/l. Nine samples, however, show concentrations above 250 mg/l. These elevated sulphate concentrations indicate some metamorphism of groundwater as it moves from the upper parts of the basin where the water is bicarbonate to the lower parts where it starts to change to sulphate and chloride type water. The majority of samples show total dissolved solids concentrations less than 500 mg/l. Twenty one samples, however, show concentrations above 500 mg/l.

An examination of the water quality database for wells completed in the overburden indicates that most of the wells have very hard water. Only seven samples show chloride concentrations above 250 mg/l, while the majority of the samples have concentrations much less than 177 mg/l. Unlike the bedrock, most of the samples collected from overburden wells have iron concentrations much less than 0.3 mg/l. Twenty samples, however, have concentrations above 0.3 mg/l.

The available record contains chemical analyses from 94 bedrock wells and 99 overburden wells. The locations of these wells are shown on Figure 20. The descriptions of the water quality data points in the bedrock and overburden are given in Tables 11 and 12, respectively. A summary of the major ion concentrations in the bedrock and overburden wells is given in Table 13.

In order to assess the differences in the chemistry of the groundwater in the bedrock and the overburden and to determine the water types, a program called DUROV Water Quality Analyzer was used. Water quality data in mg/l entered into the program are converted into equivalents per million (EPM) and percent EPM values. The EPM values are used in the computer program to calculate the ion balance and to determine the percent ion balance; the percent EPM values, on the other hand, are used to determine the dominant ions in each sample. The program generates a water type table. The percent EPM values can then be plotted on a trilinear diagram which shows the dominant cations and anions for all the samples.

Table 14 lists the input data for bedrock wells that were entered in the DUROV Program and Table 15 lists the water types for these wells. Figure 21 is a trilinear diagram showing the dominant cations and anions in bedrock samples. The DUROV analysis indicates that 68% of all samples from bedrock wells have calcium-

Figure 21. CHEMICAL COMPOSITION OF WATER IN THE BEDROCK

LEGEND

⊙ – PERCENT EPM (% ABS(error) <=10)

* – PERCENT EPM (% ABS(error) >10)

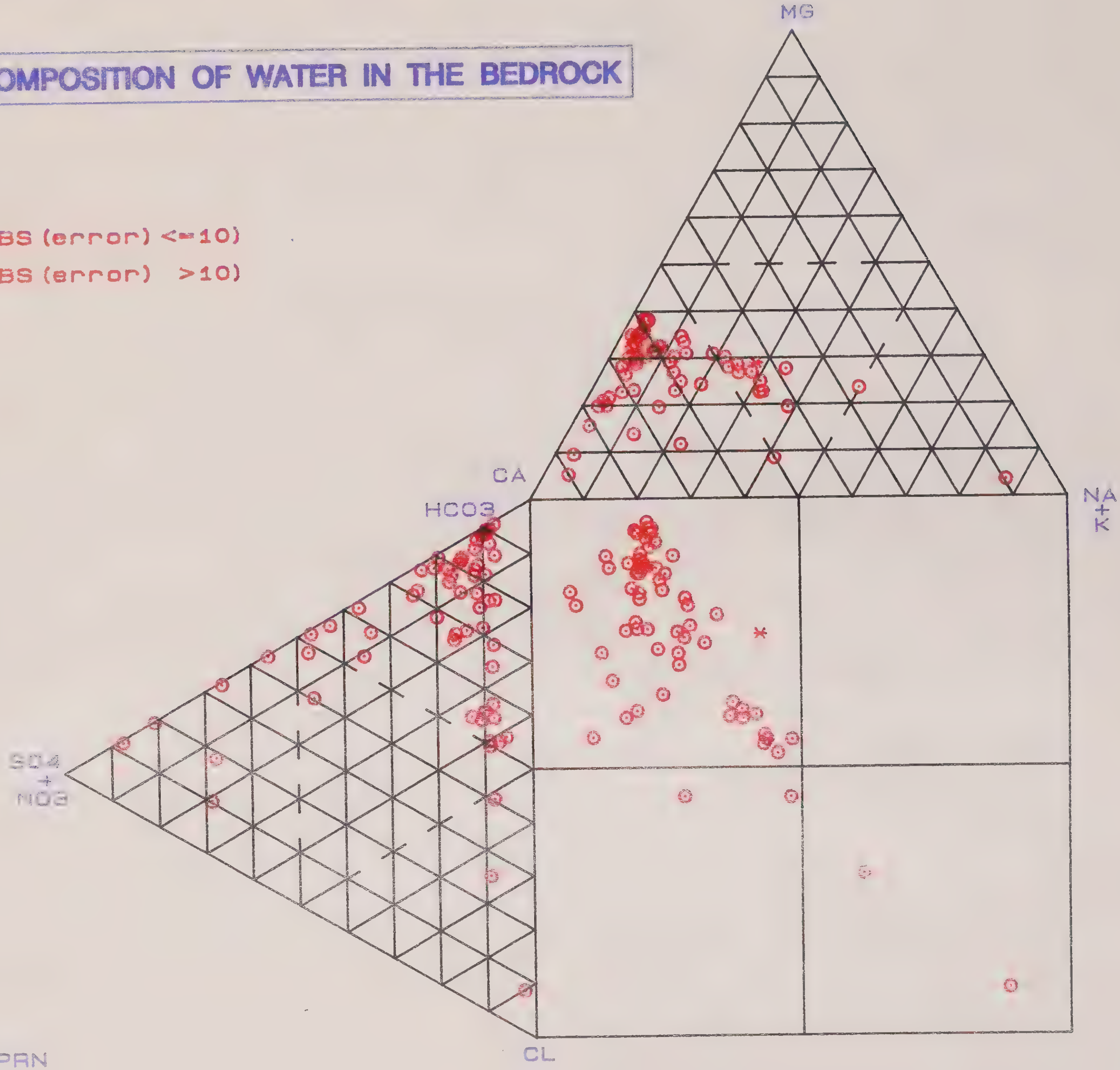


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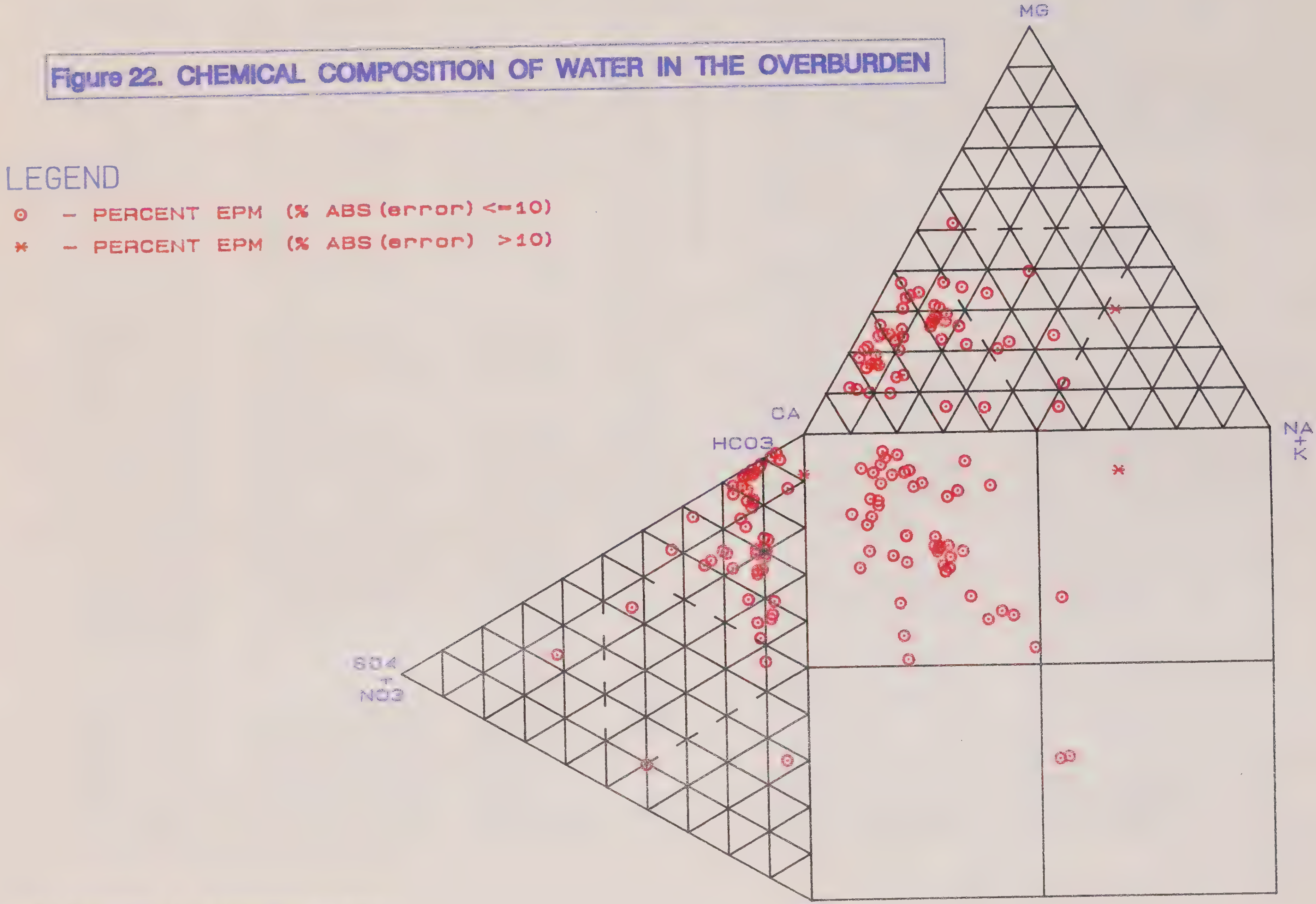
Figure 22. CHEMICAL COMPOSITION OF WATER IN THE OVERBURDEN



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bicarbonate water type and 14% have bicarbonate water type.

Table 16 lists the input data for overburden wells that were entered into the DUROV Program and Table 17 lists the water types for these wells. Figure 22 is a trilinear diagram showing the dominate cations and anions in overburden wells. The DUROV analysis indicates that the majority of water in the overburden is calcium-bicarbonate (77%) or bicarbonate (8%). Table 18 gives a summary of water types encountered in the bedrock and overburden wells.

Records of chemical analyses over extended periods of time were collected for various municipal wells. Water quality trend analyses were performed to assess the changes in groundwater quality over time for six water quality parameters. These parameters are: conductivity, hardness, nitrate, chloride, sodium, and pH. Plots of water quality trends are given in Appendix VI. An examination of these plots indicates noticeable increases in the sodium and chloride concentrations over time in most municipal wells. This is most likely due to contamination from the continued spreading of salt on roads during winter periods.

SURFACE WATER QUALITY

Fifteen monitoring stations in the Credit River Watershed are part of the Provincial Water Quality Monitoring Network (PWQMN). The locations of these stations are shown on Figure 23.

To describe the surface water quality in the study area, the existing water quality database for four parameters at all the monitoring stations was examined. The four parameters are: water temperature, chloride, total nitrate, and total phosphorus. Available data for some of these parameters date back to the late sixties and early seventies.

Use of recent data provides an indication of the present water quality conditions. That is why data for the period 1990 to 1993 was selected for statistical analysis. Table 19 provides a statistical summary for the period 1990-93 including number of observations, mean, median, minimum, maximum, first and third quartiles for the four parameters at all the sites. The percent of observations exceeding the Provincial Water Quality Guideline (PWQG) of 0.030 mg/l for total phosphorus are also included in the table.

To interpret the statistical summary and to compare one site to another, one should be aware of the fact that the variations in the number of samples collected at various sites may introduce some bias in the results. For example, most PWQMN sites would typically have between 35 and 40 observations over the period 1990 to 1993. However, the site near the mouth of the Credit River was sampled on

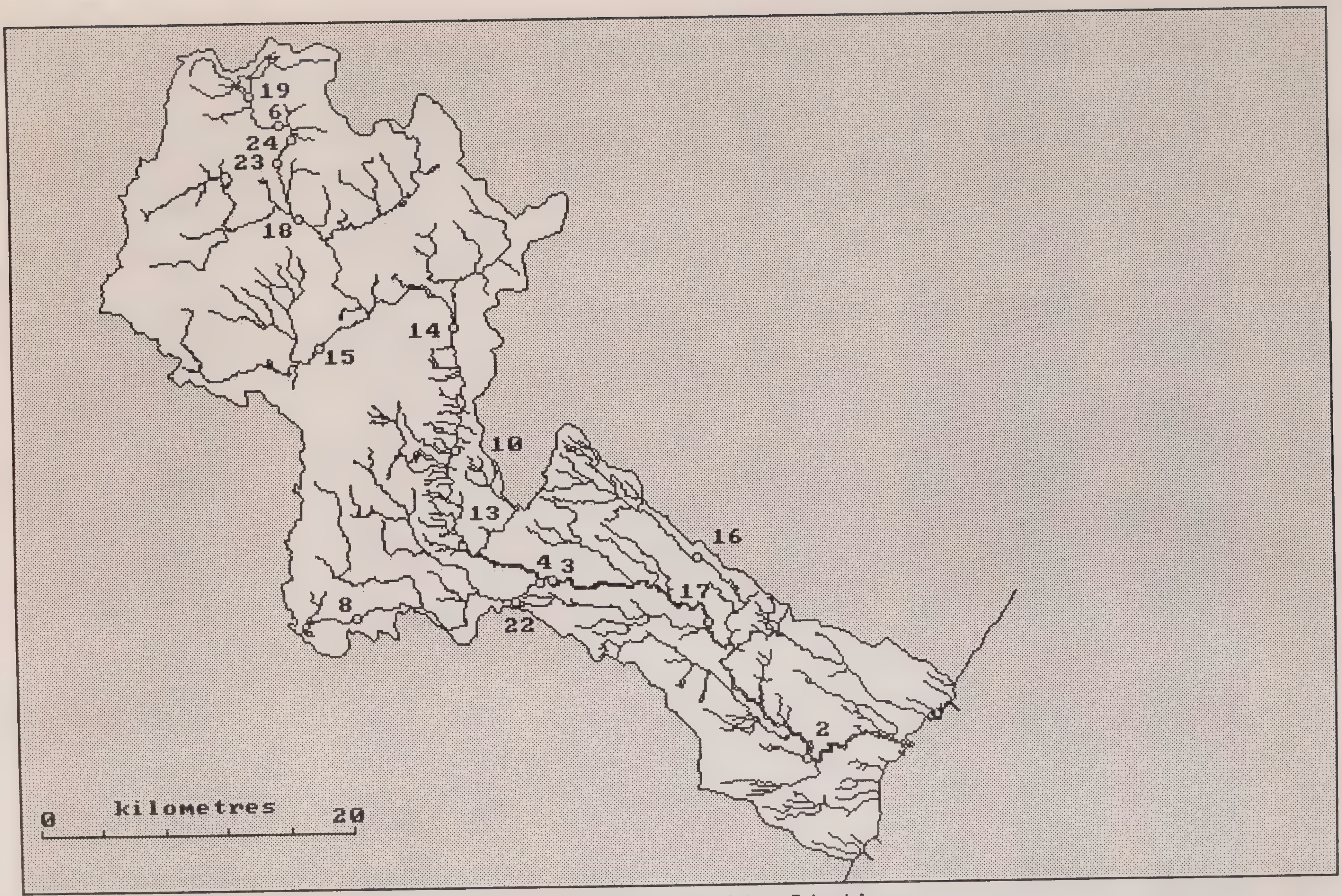

Figure 23. Locations of Surface Water Quality Stations

the order of 55 times for the same period. The extra samples were taken during the spring freshet period in order to enhance the pollutant loading estimates to Lake Ontario. This sampling regime could introduce a bias into the summary results for those parameters that are temperature dependent or flow driven.

Four sites located above and below Orangeville were also sampled on the order of 150 times from 1990 to 1993 due to a special study of the discharge from the Town's sewage treatment plant. Samples at these sites were well distributed seasonally, and their summary results should be reasonably reliable.

The areas within the watershed that exhibit good water quality include the Erin Branch, the Credit River above Orangeville and the reach of the river above the confluence with the West Branch.

Areas within the watershed that exhibit poorer water quality include the Credit River below Orangeville, Black Creek, the West Branch of the Credit River above the confluence with the main branch, and Fletcher's Creek. These areas have been impacted primarily by urban storm water runoff and discharges from sewage treatment plants.

It should be noted that point and non-point source discharges to a river and its tributaries can have significant localized impacts on surface water quality. This is particularly the case in the headwater areas and in tributaries with insufficient streamflow capacity for waste assimilation. For example, in the case of the Credit River near Orangeville, there is considerable difference in the water quality observed upstream of Orangeville compared to that observed downstream of the municipality.

The impact zone of Orangeville extends a considerable distance downstream as demonstrated by the quality data and similarities in the shape of trend plots observed at other water quality sites further downstream. Levels in the main Credit River do drop to what was observed upstream of Orangeville only when sufficient streamflow occur below Station 18 and towards Station 10. More detailes on present water quality in the study area are given in Appendix VII.

TREND ANALYSIS

The PWQMN data represent discrete time series of observations collected over irregular time intervals. The time series for many water quality parameters show high natural variability, parameter values extending over several orders of magnitude, and seasonal variations. In addition, the time series are representative of non-normal sample populations. These factors make the evaluation of trends over time a difficult task.

In 1991, a PC statistical and graphical program called TRENDS was developed by MOEE staff. The TRENDS Program is capable of identifying the water quality variations over time for the PQWMN time series.

The water quality variations in a time series can be accounted for by two main components, trend and seasonality. The trend component shows changes in the time series that may be caused by increases or decreases in the contributions of pollutant sources to receiving streams over time. The seasonal component, on the other hand, shows the changes in the time series that are caused by annual periodic variations or seasonal cycles. The TRENDS Program separates the time series into the two main components and provides a plot of the quality trend as well as a plot showing the variation due to seasonality.

Trend and seasonality plots were generated for four parameters: water temperature, chloride, total nitrate, and total phosphorus using all the available records at all the stations in the study area. The plots show the general shape of the quality trend of the four parameters and provide summary information indicating the general slope of the trend (positive for increasing trend, negative for decreasing trend, and 0 for no trend). An indication of whether or not the observed trend is statistically significant is also provided (Appendix VIII).

The trend analysis indicates that chloride levels are increasing at many of the monitored sites within the study area. Although the levels that are observed may not cause overly stressful situations for aquatic organisms, the fact that an upward trend is occurring, may be an indication of changes that are taking place within the watershed that need attention with regards to overall watershed management.

The large increase in chloride levels in the mid to late 1980's suggests that development within the watershed may be a major contributing factor. With development comes an increased potential for storm water runoff and the risk of introducing more harmful pollutants to the receiving streams. Storm water runoff can also result in changes to the flow regime and the destruction of aquatic habitat and spawning beds.

Total nitrate levels are also increasing at a number of monitoring sites within the watershed. Again, the fact that trends are increasing is an indication of changing land use activity within the watershed. Nitrate in surface waters is a nutrient that is readily taken up by aquatic plants during the growing season. The availability of excessive nutrients can lead to eutrophic conditions in rivers and streams.

The trend results indicate that phosphorus levels at most of the monitored locations have been on the decline. This decline is

attributed to the fact that phosphorus was identified as a parameter of concern in contributing to advanced eutrophication of the Great Lakes. Efforts have been made over many years to reduce phosphorus loadings. This includes the introduction of legislation in the 1970's to limit the amount of phosphate in detergents, the implementation of phosphorus removal from sewage treatment plant effluents, and a move to improve farming practises.

Even though phosphorus levels are on the decline, many of the monitored sites within the watershed continue to show significant violations of the provincial water quality guideline. This suggests that the efforts to lower phosphorus levels need to continue.

In order to preserve the natural environment and aquatic habitats, those responsible for managing growth and development within the watershed, need to be aware of the sensitive nature of small tributaries and headwater streams to anthropogenic inputs.

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